



Slow convergence: Career impediments to interdisciplinary biomedical research

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Affiliations are included on p. 8.

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Despite the long-standing calls for increased levels of interdisciplinary research as a way to address society's grand challenges, most science is still disciplinary. To understand the slow rate of convergence to more interdisciplinary research, we examine 154,021 researchers who received a PhD in a biomedical field between 1970 and 2013, measuring the interdisciplinarity of their articles using the disciplinary composition of references. We provide a range of evidence that interdisciplinary research is impactful, but that those who conduct it face early career impediments. The researchers who are initially the most interdisciplinary tend to stop publishing earlier in their careers—it takes about 8 y for half of the researchers in the top percentile in terms of initial interdisciplinarity to stop publishing, compared to more than 20 y for moderately interdisciplinary researchers (10th to 75th percentiles). Moreover, perhaps in response to career challenges, initially interdisciplinary researchers on average decrease their interdisciplinarity over time. These forces reduce the stock of interdisciplinary researchers who can train future cohorts. Indeed, new graduates tend to be less interdisciplinary than the stock of active researchers. We show that interdisciplinarity does increase over time despite these dampening forces because initially disciplinary researchers become more interdisciplinary as their careers progress.

interdisciplinarity | research careers | research workforce

As the solutions to problems facing society become more complex and pushing the boundaries of knowledge becomes more difficult, research that integrates different scientific fields is widely viewed as essential for addressing society's challenges (1–6). Boundary-spanning research (7) has different modalities, such as multidisciplinary, cross-disciplinary, interdisciplinary, and transdisciplinary (8, 9). While we regard these distinctions as important, we focus here on boundary-spanning research construed broadly without making a specific effort to distinguish modalities and, for short, refer to such work as “interdisciplinarity” (10). Interdisciplinarity has been intensely studied, especially since the 1990s (7–9, 11–13). Scientists and policymakers associate interdisciplinary research with increased knowledge production and innovation (14–16) and there is a long-standing and widespread belief in the science policy, administration, and research communities (17–21) that science needs to be more interdisciplinary or “convergent.” National and international evaluation boards have prioritized interdisciplinarity in science policy planning (10, 22–25). The NSF and NIH, as well as private funding foundations, have earmarked substantial funding toward interdisciplinarity (26–29).

The need for interdisciplinarity is seen as particularly great in biomedicine—the focus of our study—due to the complexity of biological processes and the need to solve pressing societal problems such as food sustainability, aging, and disease treatment (30, 31). To achieve these goals, biomedical research is undergoing revolutionary change in which strengthening and further development of traditional biomedical fields is complemented by the so-called “New Biology,” which involves integrating knowledge from many different subfields of biology and bringing in expertise and knowledge from other disciplines, such as physics, chemistry, computer science, and engineering (31). Such developments will inevitably lead to an increase of interdisciplinarity within biomedicine (32).

In practice, academic institutions enact their commitment to interdisciplinarity through various initiatives (33–36). On the national level, these include nationally funded research institutes, such as the NIH's Transdisciplinary Tobacco Use Research Centers (37–39). At the university level, administrators foster interdisciplinarity by creating new departments or research centers that focus on interdisciplinary themes and boundary-crossing problems (17, 26, 40). Universities also utilize joint appointments, often through cluster

Significance

There are long-standing calls for more interdisciplinary/convergent research to address society's grand challenges. Despite these calls, we still do not understand the impediments to interdisciplinary research. Our results, based on researchers with PhDs in biomedical fields, are consistent with interdisciplinary researchers often falling through disciplinary divides, thus discouraging convergent research and reducing the pool of talent to train future generations of interdisciplinary researchers. Our analysis suggests that supporting and retaining interdisciplinary researchers early in their careers would have a high value. Further changes to the funding incentives and disciplinary department structures which impede the survival of interdisciplinary researchers might help.

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hires, between departments and between departments and centers and institutes (19). Many universities have also established doctoral programs for promoting and enabling interdisciplinary training (41, 42). At NSF, the Integrative Graduate Education and Research Traineeship and its successor, the NSF Research Traineeship program, have supported interdisciplinary training of graduate students (43) helping them to develop scholarly identities as interdisciplinary scientists (44). In biomedicine, the National Institute of General Medical Sciences has prioritized interdisciplinary research as did the NIH's Common Fund.

Despite these efforts, at individual universities, the American academic system is still very much dominated by disciplines and academic departments (45). Disciplines and departments play a major role in hiring, promotion and tenure, curricular development and teaching, as well as student recruitment and retention (35) and may thus represent a significant source of inertia against interdisciplinary work. The interdisciplinary centers, institutes, and programs are often less permanent structures than departments, sometimes devised as solutions to fill in the cracks and address real-world problems. These "borderlands" (46) are often attractive and fertile grounds for scientists, especially established ones, to identify and pivot toward new research problems (47) but may not be hospitable for establishing long-term careers.

Despite all the efforts to promote and support interdisciplinary research, evidence that interdisciplinary researchers may enjoy greater visibility and higher impact (15, 48, 49), and widespread belief in the importance of interdisciplinary research for solving our greatest challenges, interdisciplinarity as a mode of knowledge production is hardly dominant, and there is an enduring perceived deficit of interdisciplinary research and researchers. Efforts to measure trends in interdisciplinarity reveal that interdisciplinarity in science is increasing over time, but only modestly, and certainly not commensurately with the publicized incentives (50, 51). The commitment to interdisciplinarity at academia's top organizational levels has a strong effect on grant applications but these efforts do not appear to transfer to increased levels of interdisciplinarity in publications (26). Projects funded under interdisciplinary initiatives often produce results that do not cut across disciplinary boundaries (25, 52). With all the efforts to promote interdisciplinary education, it is natural to expect that graduate students and young researchers would more readily engage in interdisciplinary research. Previous research has shown that this group of researchers indeed displays a high degree of interdisciplinarity (5, 27). However, research also shows that career outcomes such as placements and earnings are, if anything, worse for those who span boundaries (5, 53, 54). Furthermore, interdisciplinary research has been shown to receive consistently lower funding when competing with disciplinary research (55). From an economic perspective, such deficits are something of a puzzle because if the demand for interdisciplinary research were truly high, one would expect strong placement outcomes, which would induce an increase in supply. The resolution of this puzzle may be found in a number of case studies and conceptual frameworks examining why interdisciplinary researchers may have greater difficulties finding employment and launching their research careers (1, 41, 56, 57). For example, interdisciplinary researchers may need to overcome cultural and language differences between disciplines, as well as structural and institutional barriers. At the very outset of their research careers, interdisciplinary trainees face additional educational challenges, such as conflicting teaching styles and a need for multiple mentors (58–60). They may also face greater risks in obtaining jobs, publication, grants, and public recognition (41), especially in the short run (61). The benefits of increased citation impact come paired with the penalty of fewer papers published (15).

In addition, disciplinary-spanning papers may be disadvantaged by journal rankings (62), and interdisciplinary researchers may be less likely to have their work positively evaluated by promotion or tenure committees (41). Even Nobel Prize committees seem to favor disciplinary contributions (63). Researchers engaging in interdisciplinary work pit these considerable costs against the perceived value of the work itself. As one graduate interviewee put it, "I am dealing with the core problems of society," speaking about the widely cited association of interdisciplinary work and complex practical issues. However, the student also noted, "I am sorta' on the fringe of science" (27).

Compounding these factors, new researchers are entering a scientific workforce that is characterized by an exponential growth in practitioners and publications (64) with an increased emphasis on team science (65, 66). Such a hypercompetitive environment has led to progressive shortening of publishing careers of recent cohorts of researchers (67), leading one to ask what factors contribute to having a long and successful research career. Prior work has identified productivity (68–71), impact (72–74), and the level of specialization (75) as important factors related to career success. Comparatively less attention has been paid to another factor: the extent of interdisciplinarity. There is evidence that successful researchers tend to have interdisciplinary careers by moving from one research area to another over the course of their career, while focusing their effort on a single area at a given time (76). Furthermore, researchers tend to diversify their research interests after obtaining tenure (77). Successful researchers use collaborative networks as a way to increase benefits from intellectual diversity (78). Interdisciplinary researchers were found to play more central roles in research collaboration networks (61). And while their research has lower impact at the outset of their careers, interdisciplinary researchers in the long run show more success in obtaining funding for their research both in terms of volume and value (61). However, we still do not know whether this higher success of interdisciplinary research translates into research career longevity and whether interdisciplinarity is a win-win situation for both science at large and for the people practicing it.

Thinking of the pool of interdisciplinary researchers as a "stock," and entry, exit, and changes among practitioners as "flows," we address questions such as: How does the flow of graduates into research compare to the stock of researchers? How does the interdisciplinarity of entering researchers relate to the interdisciplinarity "inherited" from their mentors? Does the degree of interdisciplinarity of a researcher change over the career (perhaps in response to either the benefits or the pitfalls that pursuing interdisciplinary work entails)? All of these key pieces are important for our understanding of why the rate of convergence to interdisciplinary research has not been faster. We find that entering researchers are less interdisciplinary than the stock of researchers. This tendency and the lower career longevity for interdisciplinary researchers with PhDs in biomedical fields are grave impediments to increasing interdisciplinarity.

Results

To address the above questions, we study two samples. Our primary analyses comprise 154,021 researchers who received a PhD in a biomedical field between 1970 and 2013. A second sample comprises 2,612,553 papers published between 1970 and 2018, 5 y after the last graduation in our sample, to measure both citation accumulation and the gap in publishing that marks the end of a researcher's career. For both samples, we collected data on publication history using the Author-ity disambiguation of PubMed (79, 80) database. We also used ProQuest's Dissertation

Table 1. Summary statistics of variables used in the regression analysis

Variable	N. observations	Mean	SD
Citations	2,212,980	58.1	148
Interdisciplinarity	2,179,057	0.398	0.208
Career year	2,352,321	13.0	7.65
Publication year	2,352,321	1996	10.6

Note. Summary statistics of the variables in our regression. Observations are weighted by the inverse of the number of authors in our sample so that each paper in our regression has a weight of one.

and Theses database to determine the dissertation field and the year of the highest degree attained. Finally, we used data from the Clarivate Analytics Web of Science (WoS) to calculate the interdisciplinary score for the papers identified above, as well as to obtain citation counts to these papers through 2018 (inclusive) (*Materials and Methods*).

Interdisciplinarity is a multifaceted phenomenon, and therefore, it is not surprising that over the years, quantitative science studies have proposed a number of measures trying to capture it (81–83). These measures utilize different bibliographic elements: author affiliation, coauthorship, keywords, references, and citations. All of these measures rely on the classification of scientific literature. Most of the bibliometric-based studies rely on journal-level classifications of the scientific literature, despite the well-known problems of such an approach (84, 85). In this paper, we use an article-level classification of articles based on the disciplinary composition of their references that uses WoS journal-based classification as a starting point and iterative refinement (86). The interdisciplinarity measure we use in this paper follows a well-established approach, which operationalizes interdisciplinarity as the fraction of references given to papers that do not belong to the primary discipline (87–89) (*Materials and Methods*).

Lower Risk of Citation Flops for Interdisciplinary Research.

Previous results on the impact of interdisciplinary research lead us to expect that interdisciplinary research would produce papers that attract more citations (15, 48), although this relationship has also been found to be discipline-dependent (89, 90). To examine the relationship with impact in our dataset, we use a regression model to relate the likelihood of receiving a low number of citations to interdisciplinarity, controlling for individual and publication

year fixed effects (dummy variables). Note that this specification embeds linear career year and field controls. We also control for career year squared for possible nonlinear effects of seniority.

Our sample focuses on researchers with PhDs in biomedical fields with a career age between 1 and 30 y, who published papers in the period between 1970 and 2010 (inclusive). We focus on papers published through 2010 to allow sufficient time for articles to accrue citations. We collect the citations these papers accrued until 2018. We then run regressions using a linear probability model to examine the likelihood that any given article published after graduation is in the lowest quartile in terms of citations (citations ≤ 11). Table 1 reports the summary statistics of the variables we use in the regression model. The estimates reported in Table 2, Column (1), show that more interdisciplinary work has a lower probability of being a “flop” (i.e., having 11 or fewer citations). In Column (2), we add to the regression model a dummy variable equal to 1 when a paper has zero interdisciplinarity. Papers with an interdisciplinarity score of zero are significantly more likely to be flops. In the second model, the linear effect of interdisciplinarity is close to one-third the size in the baseline model. This finding indicates that about two-thirds of the effect that we estimated in the baseline model [Column (1)] is due to the difference between fully disciplinary and (even slightly) interdisciplinary articles.

We explore whether researchers who started their careers as more interdisciplinary have a citation advantage in Columns (3) and (4). To explore this possibility, we introduce in the regression model the interaction between interdisciplinarity and a dummy variable equal to 1 for researchers whose initial interdisciplinarity is above the median. Our estimates indicate that initially disciplinary researchers gain less from doing interdisciplinary research than initially interdisciplinary researchers in both specifications. Moreover, Column (4) shows that initially interdisciplinary researchers who publish entirely disciplinary papers suffer more of a penalty than initially disciplinary researchers who do so. Thus, initially disciplinary researchers have an advantage in continuing to conduct disciplinary research just as interdisciplinary researcher have an advantage in continuing to conduct interdisciplinary research. This finding takes on greater significance when combined with our next two findings.

Reduced Career Longevity for Interdisciplinary Researchers with PhDs in Biomedical Fields. While interdisciplinary work is less likely to receive low citations than more disciplinary work,

Table 2. Interdisciplinary research is less likely to receive few citations

	(1)	(2)	(3)	(4)
Article interdisciplinarity	−0.117*** (0.0019)	−0.042*** (0.0020)	−0.111*** (0.0026)	−0.037*** (0.0027)
Article interdisciplinarity × Author initially interdisciplinary dummy			−0.014*** (0.0037)	−0.008** (0.0039)
Article interdisciplinarity = 0 dummy		0.181*** (0.0021)		0.165*** (0.0025)
Article interdisciplinarity = 0 dummy × Author initially interdisciplinary dummy				0.045*** (0.0042)
N	2,160,043	2,160,043	2,160,043	2,160,043
R ²	0.17	0.18	0.17	0.18

Note. Probability of a paper falling in the bottom quartile of citations (i.e., receiving ≤ 11 citations) as a function of interdisciplinarity. Our sample comprises researchers with a career age between 1 and 30 y, who published papers between 1970 and 2010 (included). We focus on papers published through 2010 and citations through 2018 (included). Estimates are from linear probability models that control for individual and publication year effects (dummy variables, which accounts for career year and field) and career year squared. Observations are weighted by the inverse of the number of authors in our sample so that each paper in our regression has a weight of one. Article interdisciplinarity is a continuous measure of the interdisciplinarity of the article. The “Article interdisciplinarity = 0” dummy variable equals 1 for articles with an interdisciplinarity level of 0. The Author initially interdisciplinary dummy variable equals 1 for authors whose dissertation-stage work is above the median of interdisciplinarity.

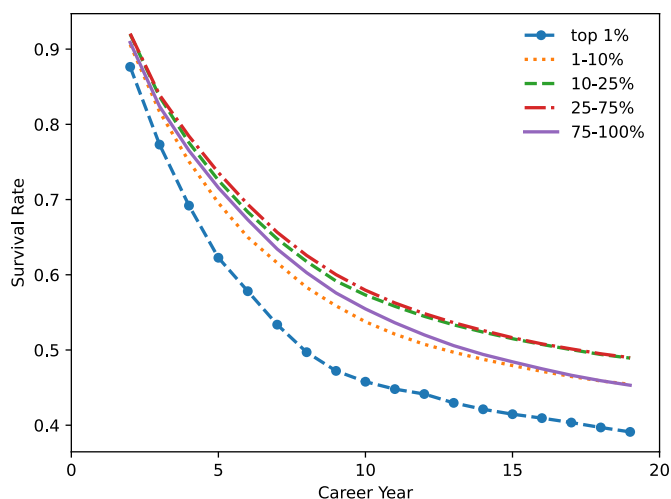


Fig. 1. Interdisciplinary researchers are less likely to continue publishing. Survival rate of researchers with PhDs in biomedical fields who graduated between 1970 and 2013 divided based on the levels of initial (dissertation-stage) interdisciplinarity. A researcher's career is considered ended when that person does not publish for a period of 5 y. Researchers with high initial interdisciplinarity (i.e., in the top 1% or 1% to 10%) have lower survival rates at all career stages.

prior research suggests that interdisciplinary work might be riskier for researchers (41, 91). One risk researchers may face is that they may find it harder to secure and retain long-term research positions (5, 54). It has also been found that early-career researchers experience significant challenges in pursuing interdisciplinary research independently (61). These challenges may be exacerbated by the difficulties associated with evaluating interdisciplinary research (92), which is adding strains (93) to a peer review system that is already fraught with problems and biases (94, 95).

To assess the relationship between interdisciplinarity and career longevity, we examine the publication “survival rate” for researchers who graduated between 1970 and 2013. We consider a researcher to have ended a publishing career if they did not publish for at least 5 y. We divide all the researchers into 5 groups based on the level of initial interdisciplinarity (top 1%, 1 to 10%, 10 to 25%, 25 to 75%, and 75 to 100%). For each researcher in our data set, we calculate their initial interdisciplinarity as the median interdisciplinarity score of all the papers they published in their “dissertation-stage” (*Materials and Methods*). We then employ survival analysis to study their research career longevity. Survival curves are calculated as the fraction of researchers within each interdisciplinarity group still publishing (i.e., still in the sample) after X years.

The results in Fig. 1 show that survival declines rapidly regardless of interdisciplinarity early in the career and more gradually as career year increases. However, the most interdisciplinary researchers (top 1% and 1 to 10%) are at a higher risk to stop publishing than their less interdisciplinary colleagues throughout their careers [interestingly, so are the least interdisciplinary/most disciplinary researchers (75 to 100%)]. While half of the most interdisciplinary researchers (top 1%) stop publishing by year 8, it takes more than 20 y for moderately interdisciplinary researchers (10 to 25% and 25 to 75%) to do the same. Most exits occur early in the career as researchers transition into faculty positions and approach tenure. This timing aligns with earlier findings that promotion and tenure criteria are among the biggest impediments to interdisciplinary research (10) and that interdisciplinarians experience more challenges in terms of promotion (96). In contrast to our results for citations, this finding indicates that interdisciplinary research is risky in terms of career longevity. This greater attrition reduces

the stock of initially interdisciplinary researchers, who have an advantage in conducting interdisciplinary research, as well as the stock of interdisciplinary researchers available to train future cohorts.

Interdisciplinarity Increases over the Career for Initial Non-Interdisciplinarians and Declines for Initial Interdisciplinarians.

How does the level of interdisciplinarity of researchers with PhDs in biomedical fields change over the career given the risks and rewards we have identified? Fig. 2 divides all researchers in the 1970 to 2013 cohorts into two groups (above and below the median in terms of initial interdisciplinarity) and plots their interdisciplinarity over the career. To ensure that what we observe is not driven by simple mechanical reversion to the mean as the result of classifying researchers as above or below the median level of interdisciplinarity, we use dissertation-stage work for classification, and study patterns starting only after this initial period (*Materials and Methods*). Fig. 2 shows that researchers who were initially above the median in interdisciplinarity experience a pronounced decline in interdisciplinarity, especially in the first few years after graduation. This change would be a logical response to the challenges interdisciplinarians face in terms of getting and maintaining jobs, including obtaining tenure. They are also consistent with interdisciplinarians expanding beyond their dissertation research area into areas that happen to be more disciplinary. By contrast, researchers who were initially below the median in interdisciplinarity quickly become more interdisciplinary. This shift might reflect the importance that the researcher community and researchers put on interdisciplinarity, which is reflected in the increased benefits to engaging in interdisciplinary research as a researcher's career progresses (78), an expansion of research interests, or even an “expenditure” of accumulated capital. Regardless of the reasons, at least at the gradual rate shown, the intellectual barriers to boundary spanning research do not seem to impede a substantial increase in interdisciplinarity over the early career for initially disciplinary scholars.

Another potential interpretation of the trends we have identified is that, as researchers advance in their careers, their name appears on more collaborative papers (papers not led by them), which may tend to move them toward the middle ground. To test

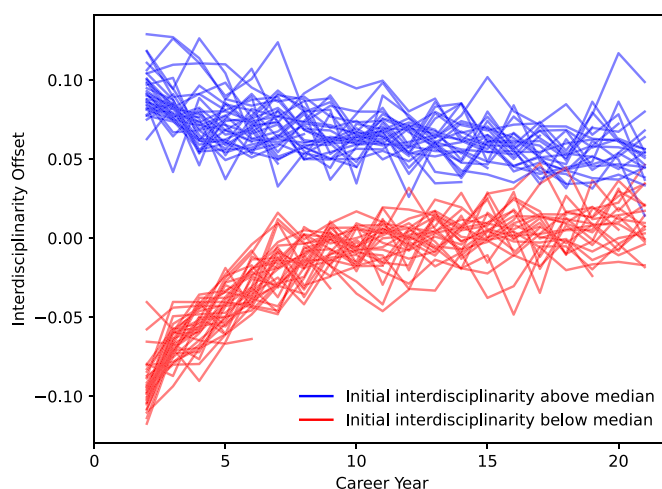


Fig. 2. Interdisciplinarity declines for initially interdisciplinary researchers and increases for initially disciplinary researchers. The figure shows trends in interdisciplinarity for biomedical researchers who start with different levels of initial interdisciplinarity. Interdisciplinarity is calculated in a relative way, as an offset with respect to what is typical for a given time period. Individual lines (both red and blue) reflect different cohorts (i.e., people who received their PhDs in a given year, including cohorts from 1970 to 2013).

whether this is the case, we repeated our analysis keeping only the papers where a researcher was either the last author or the first author and found our results to be robust. Finally, we check whether the observed trends are the result of selective attrition of people whose work is more or less interdisciplinary than others in their group (for instance, the decline in interdisciplinarity for interdisciplinarians could be driven by greater attrition of the most interdisciplinary researchers in that group). We control for attrition using individual fixed effects (dummy variables) and have found the results to be similar when we include these additional controls separately or together.

The above analyses show that researchers whose initial work has a higher level of interdisciplinarity tend to stop publishing sooner and that they shift toward less interdisciplinary work, especially, during the high-risk period (the first 10 y after graduation). On the other hand, initially disciplinary researchers shift toward more interdisciplinary work over their careers. Overall, there is a clear tendency for researchers as a whole to become more interdisciplinary as they gain experience. This arises because the increase in interdisciplinarity among researchers who are initially less interdisciplinary is greater than the decrease in interdisciplinarity among researchers who are initially more interdisciplinary. Just as the reduction in interdisciplinarity among initially interdisciplinary researchers may be a response to risk, the increase in interdisciplinarity among people who are initially disciplinary may indicate that initially disciplinary researchers are responding to what they see as the most pressing types of research as they become more established. At the same time, there might be potential inefficiencies given the results in Table 1 that researchers who are initially more disciplinary tend to have a comparative disadvantage in producing interdisciplinary work.

Advisees Inherit Interdisciplinarity from Their Advisors. One place where intellectual and career factors both manifest is in training and mentorship. Training determines the flow of people into research and advisors play a critical role in shaping the new generation of scholars (97). Therefore, one would assume that whether advisors engage in interdisciplinary work might be an important determinant of the interdisciplinarity of their advisees, especially if there are important intellectual or institutional barriers to conducting boundary-spanning work. We next examine the relationship between advisor and advisee interdisciplinarity. The decision to work with an advisor who is interdisciplinary may not be intentional but a product of coincidence or personality for some graduate students. At the same time, we caution that the analysis should not be interpreted as causal because, for instance, some people who know they want to do interdisciplinary work might seek out more interdisciplinary advisors. Furthermore, it may be the case that working in certain areas comes with higher interdisciplinarity, so interdisciplinarity is not a result of any direct influence, but rather the norm in a particular research area.

Fig. 3 plots the relationship between the interdisciplinarity scores of advisor and advisee papers. It displays the mean advisee interdisciplinarity for different bins of advisor interdisciplinarity levels. Here, for calculating interdisciplinarity scores of advisees, we exclude publications with their advisors. To account for time trends in interdisciplinarity, we control for graduation year fixed effects (dummy variables). While there is substantial variation in the interdisciplinarity of graduate students at all levels of advisor interdisciplinarity (especially because here we exclude advisee-advisor joint papers), there is a clear tendency for students of more interdisciplinary advisors to conduct more interdisciplinary research themselves. While we again caution against a causal interpretation, the results of this analysis suggest that having more interdisciplinary

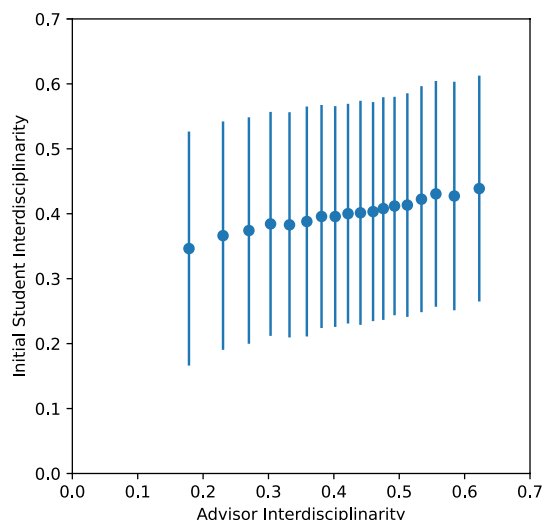


Fig. 3. The interdisciplinarity of advisees is related to that of advisors. We divided PhD recipients from 1970 to 2013 into 18 bins based on the interdisciplinarity of their advisors, with an equal number of students in each bin. The figure presents the mean advisee initial interdisciplinarity for different categories of advisor interdisciplinarity, with bars showing one SD. Note that advisee papers included in this analysis exclude joint papers with the advisor.

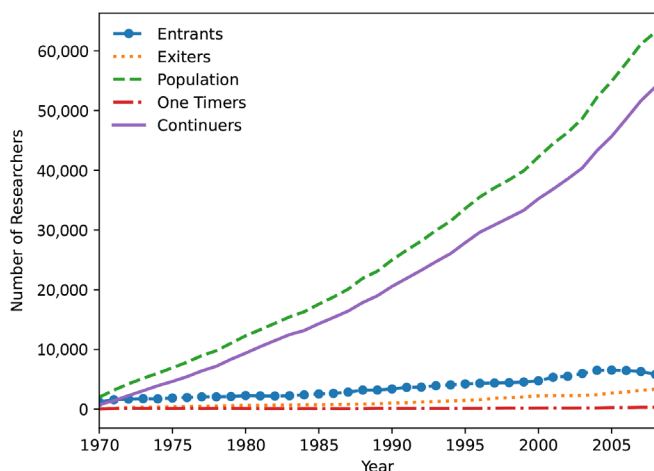
advisors may help produce more interdisciplinary researchers. If so, the attrition of interdisciplinarians shown in Fig. 1 reduces the stock of researchers available to train future interdisciplinary researchers.

Entrants Reduce the Level of Interdisciplinary Research. How do the factors that we have investigated—the training of new researchers, their survival, and the trends in interdisciplinarity over the career—jointly determine trends in interdisciplinarity over time? The answer to this question hinges on stock-and-flow dynamics, including how the interdisciplinarity of new researchers (the inflow) and the exit of existing researchers (the outflow) compare to the level of interdisciplinarity of continuing researchers (the stock) and the change in their interdisciplinarity.

Fig. 4 quantifies the sizes of the stocks and flows for such analysis. We take the population of researchers publishing in each year and divide it into four mutually exclusive groups: 1) entrants, who publish for the first time in the focal year and again in some later year; 2) exiters, who publish for the last time in the focal year and who have published in an earlier year; 3) one-timers, who only ever publish in the focal year; and 4) continuers, who publish in the focal year, at least one earlier year, and at least one later year. Fig. 4*A* shows the enormous growth of the biomedical research workforce and also that the overwhelming majority of people publishing in each year are continuers so that their level of interdisciplinarity inevitably is an important driver of interdisciplinarity overall. There are also considerably more entrants than exiters (including one-timers), which is how the workforce grows.

Fig. 4*B* plots trends in interdisciplinarity over time. The speed of convergence varies over time as a function of entry, exit, and changes in the level of interdisciplinarity among the various groups. Specifically, while there is an overall increase, there is a period of stagnation in the late 1980s to early 1990s, followed by continual increase since. As expected, overall interdisciplinarity tracks that of continuers quite closely. The average interdisciplinarity of exiters and one-timers are relatively noisy given their small population shares, but they also tend to track the overall level of interdisciplinarity. Entrants are, however, considerably and consistently less interdisciplinary than the population. While

A



B

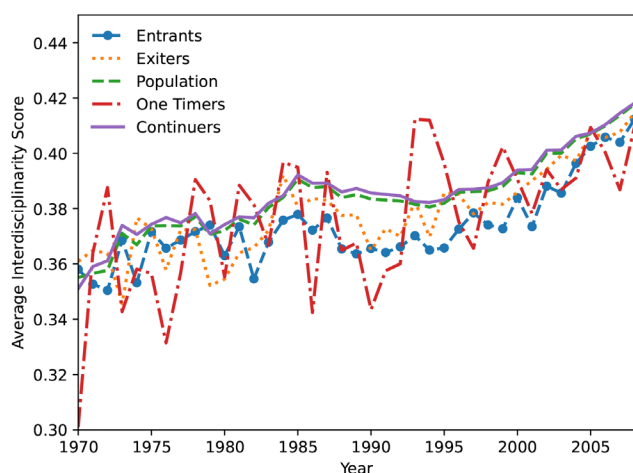


Fig. 4. Stock and flow analysis of changes in interdisciplinarity. This figure quantifies the sizes and levels of interdisciplinarity of the stocks and flows among publishing biomedical researchers between 1970 and 2010. We take the population of researchers publishing in each year and divide it into four mutually exclusive groups: 1) entrants, who publish for the first time in the focal year and again in some later year; 2) exitters, who publish for the last time in the focal year and who have published in an earlier year; 3) one-timers, who only ever publish in the focal year; and 4) continuers, who publish in the focal year, at least one earlier year, and at least one later year. Panel A shows that most publications are by continuing researchers and that entrants outnumber exitters. Panel B shows that entrants are less interdisciplinarity than the other population groups.

the lower level of interdisciplinarity among entrants may not be surprising given the career incentives we have shown, it is deeply problematic. While one might expect and hope that the newest researchers would undertake the most interdisciplinarity research and pull research in that direction, that turns out not to be the case on average. The fact that entering researchers are less interdisciplinarity than the stock of researchers also poses a grave challenge to increasing interdisciplinarity. In particular, it means that changes over the career in the interdisciplinarity of continuers (reported in Fig. 2) must both offset the tendency of new researchers to reduce interdisciplinarity and raise interdisciplinarity overall, slowing convergence. Perhaps ironically, the growth in interdisciplinarity is driven by originally moderately to highly disciplinary researchers becoming more interdisciplinarity over time (the red curves in Fig. 2). While this may be a good strategy for the longevity of one's career, these researchers appear to have

a comparative disadvantage in producing interdisciplinarity research, as highlighted in Columns (3) and (4) of Table 1.

Discussion

Our study examined the stock and flow of interdisciplinarity researchers with PhDs in biomedical fields. We studied the degree of interdisciplinarity over the course of publishing careers and the relationship between the interdisciplinarity of advisors and their advisees. An advantage of focusing on a single field is that it reduces field differences. We chose biomedical research for a number of reasons. First, it is at the forefront of the discussions on the convergence, since a large number of pressing problems require biomedical expertise. It is also one of the most active research areas in terms of paper output, so it is well represented in bibliographic databases and enjoys a significant level of funding. Finally, researchers with PhDs in biomedical fields are a large and important research population. At the same time, we acknowledge that other areas of science with their own knowledge production practices, evaluation norms, and composition and dynamics of researcher demographics may behave differently when it comes to interdisciplinarity.

Our findings suggest that although interdisciplinarity research is valuable, the supply of interdisciplinarity researchers may have been held back by career incentives that slow stock-and-flow dynamics. Early career researchers have tended to engage in less interdisciplinarity research than more experienced researchers for two reasons. There has been a tendency for each generation of researchers with PhDs in biomedical fields to initially be less interdisciplinarity than the population. Moreover, this gap has been compounded by (and is perhaps at least partially a consequence of) interdisciplinarity researchers stopping publishing at considerably higher rates than more disciplinary colleagues. Offsetting these patterns, interdisciplinarity research has increasingly been produced by researchers who, at the outset of their careers, conducted moderately to highly disciplinary research, but whose research has become more interdisciplinarity over time. These patterns are not recent phenomena, but hold for decades of researchers, although they may change in the future.

The relatively weak career outcomes of early-stage interdisciplinarians in biomedical research are something of a puzzle and deeply problematic if interdisciplinarity research is indeed as important as claimed and suggested by our results. They manifest in the form of lower initial salaries of interdisciplinarity researchers, their increased likelihood to take postdoc positions, less stable employment, and increased likelihood to stop publishing after graduation compared to graduate students with disciplinary foci (5, 30). The riskiness of interdisciplinarity research may indicate that interdisciplinarity researchers are more often operating around and potentially falling through the disciplinary divides in the system, discouraging convergent research and reducing the pool of talent to train future generations of researchers in convergent work.

Our study is longitudinal. It follows cohorts of researchers over the span of 40 y. Over that period, biomedical research itself has undergone significant changes, including the emergence of "genomics" and current integration of biomedical fields with physics, computer science, and engineering. While maybe the most prominent, this is not the only area undergoing convergence with computer science and engineering. Research should be conducted to examine more closely these types of convergence and their effect on gender balance, power structures and prestige, problem choice, reward structures, research team composition and dynamics and their impact on boundary-crossing work. Some of these boundary-crossing research efforts result in the formation of new disciplines which

change the structure and dynamics of the entire scientific enterprise. These processes and their effect on the careers are important but are beyond the scope of this paper.

There are additional factors that are likely to be important that we have not examined in this study, but hope that future studies will. One is gender, where different studies have reached opposing conclusions—from there being no difference in who engages in interdisciplinary work to either men or women doing more interdisciplinary work (5, 15, 98, 99). While gender balance in biomedical fields as a whole has been historically more or less equal, the New Biology is attracting researchers from traditionally male-dominated fields. This may lead to a potentially important difference between biomedicine and other fields whereby it is men (32, 99) rather than women (100) who do more interdisciplinary work. Also, future work should examine whether gender mediates the relationship between interdisciplinarity and career longevity (101).

Other important factors we have not taken into account are well-documented and long-standing gender, ethnic, and institutional biases associated with peer review (94, 95). Peer-review bias is likely to have a role in making it more difficult to publish, especially in the most visible venues, and consequently to obtain promotion and tenure due to discipline-focused evaluation criteria (102). These factors might be important for explaining why early interdisciplinary researchers with PhDs in biomedical fields have an 8-y “half-life,” which is close to the time when someone with a postdoc could be approaching a tenure review.

Another factor, which might have contributed to greater attrition of interdisciplinarians is the departmental structure of universities, which rewards and incentivizes disciplinary work, imposing boundaries for the flow and advancement of interdisciplinary researchers. In addition, other field-level factors (such as the availability and reliance on funding, length of postdoctoral training, size, and importance of research teams) could shape how interdisciplinarity affects career outcomes. For instance, much of the sphere we study is heavily reliant on support from the NIH. While the NIH has a reputation for conservatism in its funding, it also has programs to support interdisciplinary research (e.g., the Common Fund). Interdisciplinary work is also often at the borderland, and thus perceived as more risky, hindering opportunities for funding. With all these impediments it is not surprising that the researchers with longer careers, who have accumulated disciplinary capital and professional and social resources (27) can afford to engage in the boundary-crossing work which is too risky for the newcomers.

Our study raises a question: How might convergence toward boundary-crossing work be accelerated? There are laudable programs in place to support interdisciplinary trainees (44, 103, 104), but our analysis suggests that finding ways of supporting and retaining the interdisciplinary researchers that we do produce early in their careers could have a high value. Doing so would reduce the exit of interdisciplinary researchers, directly increasing interdisciplinarity. It would also leave more interdisciplinary advisors to train future researchers, and it would surely provide greater incentives for interdisciplinary research.

Materials and Methods

Data. We rely on three major sources of data: publication data from the Authority disambiguation of PubMed, measures of interdisciplinarity of publications generated from the WoS, and data on dissertations from ProQuest's Dissertations and Theses database. Author-ity data (79, 80) allow us to identify unique authors. The Author-ity data set has been completely recomputed and updated to cover PubMed publications up to 2018 and is estimated to have an accuracy of 98%. We complement these data with Authorlink, which links the publication clusters

in Author-ity to ProQuest, to determine the dissertation field and year of the highest degree for researchers. We used ProQuest first to identify individuals who obtained a PhD degree and whose dissertation main subject is related to a biomedical field to ensure that their papers are more likely to be covered by PubMed. Based on the number of articles per dissertation, we kept dissertations that fall into the following ProQuest categories: Anthropology, Medical And Forensic; Anthropology, Physical; Chemistry, Biochemistry; Chemistry, Pharmaceutical; Engineering, Biomedical; Parasitology; Psychology, Cognitive; Psychology, Physiological; Psychology, Psychobiology; Nutrition; Pathology; Biology; Aquatic Sciences; Genetics; Biophysics; Physics; Health Studies; Gerontology; Medicine; Immunology; Nursing; Pharmacology; Public Health; Toxicology; Recreation; and Statistics. The online materials provide a crosswalk between the subjects listed in the Authorlink and our aggregated fields.

We used PubMed IDs to obtain bibliographic data on PubMed publications from the Clarivate Analytics WoS. For each publication, we used WoS data to calculate the interdisciplinarity score and track the number of citations received. Finally, we used the linked PubMed/ProQuest/WoS dataset to select the sample. The sample includes researchers meeting three criteria: a) they published at least one paper in the dissertation-stage of their career, defined as the period between 5 y prior to and 1 y after obtaining their degree (to allow for a 1-y publication lag); b) their first and last degrees in Authorlink are no more than 8 y apart (to reduce name disambiguation errors); and c) at least one of their papers has an interdisciplinarity score. (We chose an 8-y window between multiple degrees that appear in the ProQuest database to allow for a 5- or 6-y PhD process plus 2 or 3 y between the previous dissertation and starting a new degree.) Finally, we defined career year (or career age) of researchers as the number of years elapsed since graduation, and career length as the career year at the time of their last publication. Throughout the paper when we refer to “career,” we therefore refer to the publishing career. We consider a publication to be the last and the publishing career to have ended if there has been no publishing activity for at least 5 y. This also means that we can determine career lengths only for researchers who stopped being active prior to 2014. In the analysis, we bundle together all the publications in the dissertation-stage and mark it as career age 0. The final dataset includes 154,021 researchers who received a PhD in a biomedical field between 1970 and 2013, and 2,612,553 unique papers between 1970 and 2018. We use papers 5 y after the last graduation in our sample to measure both citation accumulation and the gap in publishing that marks the end of a researcher's career.

One variable that is missing from our data is gender. Various studies have highlighted the importance of this factor and have reached different conclusions regarding the relationship between gender and interdisciplinarity (5, 15, 98, 99).

Interdisciplinarity Measure. Our interdisciplinarity measure is an article-level classification based on the disciplinary composition of references using the WoS journal-based classification as a starting point and iterative refinement (86). Furthermore, we are interested in interdisciplinarity that crosses boundaries among broad research areas. Therefore, for calculating our measure we used 14 broad disciplines into which ~250 WoS subject categories were grouped. We classified all the papers into a single category based on the discipline (one of the 14 broad research areas) that is most frequently found among the references. We then proceed to calculate a straightforward interdisciplinarity score for each article as the fraction of references that does not belong to the primary discipline:

$$I = 1 - \frac{\eta_{ref, disc}}{\eta_{ref, total}}$$

For a given article, the interdisciplinarity score can take a value $0 \leq I < 1$ (i.e., between 0 and 100%). We then use interdisciplinarity scores of papers to calculate interdisciplinarity scores for the researchers. For each researcher in our dataset, we calculate their initial interdisciplinarity as the median interdisciplinarity score of all the papers they published in their dissertation-stage, as defined above. When we relate the interdisciplinarity of advisees to that of advisors, we exclude advisee publications with their advisors. We measure interdisciplinarity of researchers after the dissertation-stage annually by taking the mean of interdisciplinarity scores of publications they published in each year.

Changes in Interdisciplinarity over Researchers' Careers. To study changes in interdisciplinarity over a researcher's career, we analyzed cohorts of researchers from 1970 until 2013. We define a cohort as researchers who obtained their

last doctorate in a given year. Once the cohorts have been identified, we divide all of the researchers of a given cohort into two groups: above and below the median in terms of initial interdisciplinarity. To address changes in the level of interdisciplinarity over time, rather than analyzing raw interdisciplinarity scores, we examine relative differences (offset) between median interdisciplinarity for papers in a given year and average interdisciplinarity of the two groups shown.

Data, Materials, and Software Availability. Code data have been deposited in NBER Public Use Data Archive (105). WoS and ProQuest Dissertations & Theses data by Clarivate Analytics is available for cost from <https://clarivate.com/webof-sciencegroup/solutions/web-of-science/> (106). The Author-ity data are available for free from: <https://databank.illinois.edu/datasets/IDB-2273402> (107).

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