Importance of undergraduate institution prestige in physics faculty hiring networks

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Reforming the professionalization experiences of future faculty members, including their undergraduate experience, provides a possible means to create scalable change in higher education. However, this requires an understanding of where faculty undergraduate training occurs. We analyze data from 7748 tenure-line faculty members across 611 U.S. physics departments, including their undergraduate alma mater and their employer university. The resulting undergraduate professionalization network reveals a prestige hierarchy similar in strength to those previously found in hiring networks at the Ph.D. level, indicating that the road to faculty jobs begins during undergraduate admissions. Furthermore, 42% of physics faculty members earned their undergraduate degrees from institutions outside of the United States. These results reinforce the importance of institutional prestige in academia and offer a potential strategy for driving systemic change.

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I. INTRODUCTION

Postsecondary physics education faces a number of persistent challenges, including the lack of diversity among physics faculty and professionals [1–4] and the slow adoption of research-based instructional strategies (RBIS) [5]. Efforts to address these issues include an increasing number of change initiatives [6–10]. These initiatives are often implemented in individual classrooms, departments, or universities, where the scope limits the potential impact of each initiative. Unfortunately, the issues targeted by these change initiatives are deeply engrained in systemic processes and structures that extend beyond the scope of individual universities or departments, reaching into the larger interinstitutional network of universities. Viewed at this scale, reform created by even the most successful initiatives represents a small drop in a large bucket. Thus, expanding the influence of change initiatives requires a perspective that considers how they integrate into the larger interconnected university system. Understanding this system may offer the potential to expand localized change efforts into more widespread and enduring reform.

In this study, we examine interinstitutional patterns and dynamics from a systems-level perspective. Specifically, we examine the patterns of influence between universities that result from the movement of faculty who are initially socialized at one institution and later work at another. Previous studies have explored these patterns in terms of where faculty earned their doctoral degrees [11,12], but no research has yet examined where faculty obtained their undergraduate degrees. We broaden the scope of this work by emphasizing the socialization that occurs during undergraduate education, which is crucial for promoting diverse representation in physics and influential in shaping how faculty teach.

A. A systems-level framework for change

Postsecondary reform initiatives benefit from the adoption of systems-based theoretical frameworks [13–17]. Most often, these frameworks conceptualize faculty communities, individual departments, or universities as complex systems [13,18]. This framing is critical for designing, executing, and studying initiatives that target these different systems [17]. However, it is critical to recognize that each of these systems is not isolated. They are part of a larger interconnected system that involves other communities, departments, and universities. A critical process that connects this larger system and perpetuates undesirable cultures

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that change initiatives often seek to address, including those that promote the lack of diversity in physics and hinder the adoption of RBIS, is the faculty production system.

The faculty production system determines who becomes a professor and how they fulfill their responsibilities. It involves two processes: the professionalization and training of individuals within a specific discipline, as well as a series of selection events. Professionalization involves years of formal education and immersion in one's discipline and academic norms. This process starts during undergraduate studies [19,20], continues through doctoral and postdoctoral training [21–23], and extends throughout one's career as faculty [24]. Selection events determine who advances to faculty positions. These occur at critical junctures, like undergraduate and graduate school admissions, as well as recruitment and hiring for faculty positions.

Professionalization and selection are interdependent. The criteria used at selection events favor candidates who embody and uphold established disciplinary norms, including values, beliefs, and practices that signal disciplinary legitimacy. These norms, both implicitly and explicitly, influence acts of mentorship and advising that shape the professional development of future faculty [25,26]. For example, the evaluation criteria used during the recruitment and selection of faculty have traditionally emphasized research excellence, often neglecting the importance of prioritizing teaching [27,28]. This emphasis on research is reflected in the admissions criteria of graduate schools, which prioritize a candidate's research aptitude. This has traditionally been assessed based on graduate record examination (GRE) scores and evidence of previous research experience [29,30]. These norms may persist because the faculty and administrators who institute them were socialized within the same system, were selected for their ability to excel in it, and are responsible for professionalizing and selecting the future generation of faculty and administration. Consequently, this creates a self-perpetuating evolutionary system in academia that propagates and spreads discipline-specific cultures and norms [31].

This system of professionalization and selection drives a pattern of institutional isomorphism, where organizations become more similar to each other over time [32]. This occurs in academia where most universities uphold values and practices similar to those of prestigious, research-focused institutions [32–36]. This pattern is problematic as it can stifle innovation and hinder the spread of new practices and policies [37–39], including those that promote equity [40] and improve student learning [41]. For instance, institutionalized procedures used in doctoral admissions, like the reliance on GRE scores, put women and applicants from historically marginalized groups at a disadvantage [42–46]. Similar discrimination occurs as a result of various normative procedures used during faculty recruitment and hiring [47–49].

Disrupting the problematic cultures propagated by isomorphism requires understanding the mechanisms that drive it. Here, we consider one of the key interactions in this system: the movement of individuals between universities. Universities recruit graduates from other universities while their own graduates go on to work at other universities. As a result, the faculty and higher administrators at each university represent a range of academic training experiences from a selection of other universities. As universities hire new faculty, they weave a larger interinstitutional network that reflects the influence of values, skills, and knowledge imparted by each faculty's alma maters. The structure of these networks, in turn, reflects the flows of influence that lead to institutional homogenization.

B. Focus on undergraduate training

Previous studies have investigated the institutions from which current tenured and tenure-track faculty received their Ph.D. and have shown that the majority of faculty received their Ph.D. from a small subset of elite universities [11,12]. An investigation of the emergent hiring network, which connects universities based on where their faculty earned their Ph.D., reveals a prestige hierarchy; it is more likely for someone to work at a university less prestigious than their Ph.D. institution than one that is more prestigious. This suggests that admission to graduate programs at the most prestigious universities plays a crucial role in determining who becomes a professor, while the doctoral training at these institutions shapes the knowledge, skills, and values of those professors.

While doctoral training plays a crucial role in the professional development of faculty, it is not the only factor that determines who becomes faculty or the cultural beliefs and values they hold. Undergraduate experiences also matter. For instance, these experiences can be exclusionary for students from historically marginalized groups, leading them to leave the field because of overt signals of exclusion [1–4] or more subtle biases like misaligned cultural values. For example, first-year students are more likely to become physicists if their attitudes about physics and learning physics are already aligned with those of physics experts [50,51]. This tends to give an advantage to white and male students who often enter college with attitudes that are more closely aligned with physics experts [3]. Undergraduate experiences also influence how faculty approach teaching, with instructors often referencing their own past experiences as students as contributing factors to how they teach [52–55]. However, despite the importance of undergraduate training, no investigations to date have examined the network of undergraduate professionalization that connects hiring universities to the undergraduate institutions of their faculty.

The collection and analysis of faculty hiring networks have facilitated research that extends beyond general descriptions, enabling more comprehensive examinations of the sociology and evolution of science. These studies examine the development of academic prestige hierarchies [56], their impact on the spread of scientific ideas [57], and their consequences for the persistence of gender inequities [57,58]. Similar studies of the undergraduate professionalization network in physics can extend this type of research to consider the important and distinctive role of undergraduate experiences in understanding the challenges facing the discipline and in identifying strategies to promote reform.

C. Research goal

In this paper, we describe the undergraduate professionalization network of physics faculty. This network illustrates how universities are connected by where their current tenured and tenure-track physics faculty earned their undergraduate degrees and thus reflects patterns in institutional influence via professionalizing faculty at the undergraduate level. Given that physics faculty tend to earn their undergraduate degrees from physics departments, the institutional influence represented by this network largely reflects department-specific effects on professionalization.

II. METHODOLOGY

A. Data collection and preparation

Data collection followed a snowball method starting with an initial set of universities in the United States whose physics departments graduated at least one physics Ph.D. in 2018 according to the integrated postsecondary education data system (IPEDs) [59]. A list of tenured and tenure-track faculty was identified for each of these departments, and publicly available sources like departmental and personal web pages were used to collect information regarding where each faculty member earned their baccalaureate and doctoral degrees. We then repeated these data collection procedures for all U.S. universities from this list of alumni institutions where data had not yet been collected. This collection procedure was repeated until no new universities were discovered. Metadata about universities were collected from IPEDs [59]. Further information about collection procedures can be found in the Appendix A.

In total, data were collected from 611 U.S. physics departments, totaling 7748 tenured and tenure-track faculty. Information regarding where faculty earned their undergraduate degree and Ph.D. was found for 97.7% of faculty in this study. Collectively, these faculty earned their undergraduate degrees from 1226 different universities and their Ph.D. from 595 different universities spanning 102 countries. In total, 55.6% of faculty earned both their undergraduate and doctoral degrees from U.S. institutions and 42.0% earned at least one degree from a non-U.S. institution.

Once collected, data regarding where faculty currently work and where they earned their undergraduate degrees were converted into a valued network edge list that collates how many tenured or tenure-track physics faculty working at each university earned their undergraduate degree from each other university. The same conversion was performed for where faculty earned their Ph.D., though our analyses focus primarily on undergraduate alma maters.

B. Analyses

1. Measuring imbalance

We calculated the Gini coefficient to examine the level of imbalance in where faculty earned their undergraduate degrees. Gini coefficients are a commonly used measure of wealth inequality [60]. Values range from 0, which represents complete equality (i.e., everyone has the same amount of wealth) to 1, which represents complete inequality (i.e., one individual has all the wealth). These coefficients represent the ratio of (i) the area that lies between the Lorenz curve (i.e., the cumulative income distribution) and the line of equality ($y = x$), over (ii) the area under the line of equality. In our application, instead of measuring how equitably wealth is distributed among a population, it measures equity in the number of professors who earned their undergraduate degrees among the population of undergraduate-granting physics programs. In this case, a value of 0 would represent each university having produced an equal number of faculty, while a value of 1 would represent the case where all current faculty earned their undergraduate degrees from the same university. We further examined this distribution by graphing an inverted Lorenz curve of these data [60].

2. Hub and authority scores

Hub and authority scores for each university were calculated using the hyperlink-induced topic search (HITS) ranking algorithm [61]. The HITS algorithm was originally developed to measure the importance of web pages by (i) their prominence in linking to other web pages that hold authoritative information (i.e., high hub score) and (ii) how authoritative the information on that web page is (i.e., high authority score). However, these metrics are useful in the current context and have previously been used to study the hiring and placement of Ph.D. in political science [62]. In the current application, the meaning of “hub” and “authority” differs slightly from their original usage. Universities with high hub scores are those that have graduated many undergraduates who now work at universities with high authority scores. Universities with high authority scores are those that have hired many faculty who earned their undergraduate degrees from universities with high hub scores. Thus, hub scores identify universities that are particularly influential through the training of undergraduates, while authority scores identify which university’s faculty rosters are largely made up of faculty from these hub schools. These hub and authority scores are iteratively calculated. Each university p starts with $\text{auth}(p) = 1$ and $\text{hub}(p) = 1p$. Then, authority scores are updated for each university based on the hub scores of each university q who have former undergraduates who are currently professors at university p as follows.

$$\mathrm{auth}(p) = \sum_{q \in p_{\mathrm{hire}}} \mathrm{hub}(q),$$

where p_{hire} represents universities that have graduated undergraduates who now work at university p. Hub scores are then updated as follows:

$$\mathrm{hub}(p) = \sum_{q \in p_{\mathrm{grad}}} \mathrm{auth}(q),$$

where $p_{\mathrm{grad}}RRR$ represents other universities where university $p's$ alma mater now work as faculty.

Hub and authority scores are normalized as part of each iteration to enable convergence. We calculated hub and authority scores using the *igraph* package in [63].

3. Blockmodel

Blockmodel procedures were used to partition university nodes based on approximate structural equivalence. Two universities are considered structurally equivalent if both the set of universities that employ their undergraduates and the set of universities that train their current faculty are identical [64]. We used approximate structural equivalence instead of true structural equivalence because true structural equivalence is rarely observed, including in our case [65]. (Dis)similarity was measured using Euclidean distance. This method treated edges as binary and ignored edge weights in determining the level of (dis)similarity in how universities are tied to one another. Treating edges as binary makes this model less sensitive to department size, where departments and programs that either have many faculty or many undergraduates would be more likely to form strong clusters based on their increased likelihood of having multiple connections to other institutions. This decision also makes the model less sensitive to placing universities with many self-hires into their own unique clusters. Structural equivalence scores were calculated using the *sna* package in [66].

This study is focused on the U.S. university system. However, given the abundance of non-U.S. universities from which physics faculty earned prior degrees, it was necessary to include non-U.S. institutions in the model. Due to logistical constraints, we did not collect information about faculty across the 669 non-U.S. universities in the network. Thus, we included these non-U.S. universities in a simplified manner by recording them to represent a single "non-U.S." university for these procedures.

Clusters were generated using Ward's method, which pairs universities sequentially based on (dis)similarities in their structural equivalence. This dendrogram was used in deciding to partition the network into six equivalence classes or blocks. See the Appendix for the dendrogram and resulting image matrix of the block model.

Ideally, a block model helps to make sense of the network data and the different structural roles that exist in the network. To help assess the adequacy of our block model, including the decision to partition six blocks, we investigated metadata about universities within each block. Metadata about universities were downloaded from the IPEDs database [59] and aggregated by university block membership. Aggregated statistics about universities within each block were examined to evaluate the credibility of the block model.

4. Network visualization

The structure of the network was examined using an image matrix of the block model and a series of sociographs. The image matrix graphically depicts the density of ties that exist between universities in different blocks regarding where their faculty earned their undergraduate degrees. Patterns in image matrices are often indicative of commonly found network structures [67]. The network of universities was graphically examined through a series of sociographs containing varied numbers of universities based on their block membership. Sociographs were plotted using the *sna* package in [66] using the Fruchterman-Reingold force-directed layout.

III. RESULTS

A. Imbalance in where physics faculty earn their undergraduate degrees

Most physics faculty members who earned a degree from a U.S. institution did so from a small proportion of U.S. institutions. For the professionalization of future physics faculty members at the undergraduate level, the Gini index is 0.66. This imbalance is visualized with an inverted Lorenz curve (Fig. 1), where the $y = x$ line represents perfect equality, and the degree of deviation from this line represents the inequality in faculty production. This level of imbalance is mirrored at the doctoral level, where the Gini index is 0.69, which is within the range of prior research on faculty hiring networks [12]. While there are no established guidelines to characterize the magnitude of the observed imbalance, it is noteworthy that it follows the Pareto principle, with approximately 20% of U.S. universities having trained approximately 70% of all tenured and tenure-track physics faculty.

B. University roles in the professionalization network

To study large-scale patterns on where faculty professionalization takes place, we generated a directed and valued network from our data where nodes represent universities that are connected by where their current faculty earned their undergraduate degrees. We identified structural positions occupied in this professionalization

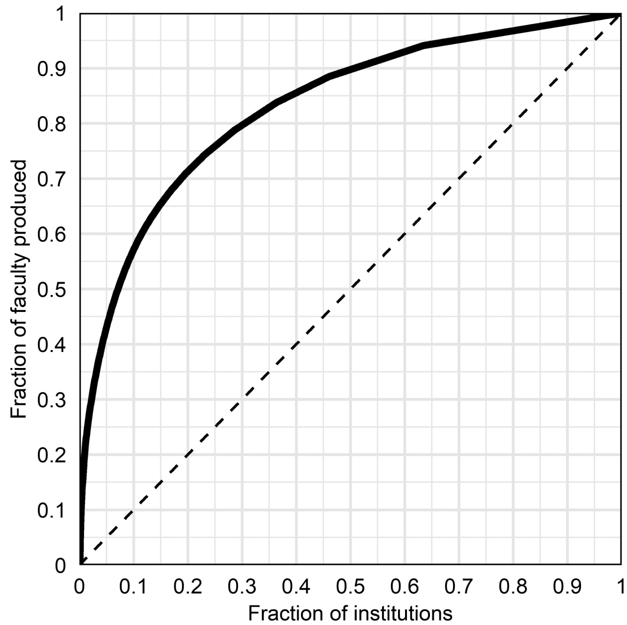

FIG. 1. Inverted Lorenz curve of faculty who earned their undergraduate degrees from U.S. institutions. The majority of tenured and tenure-track U.S. physics faculty earned their undergraduate degrees from a small fraction of physics degree-granting U.S. institutions.

network by partitioning universities into equivalence classes through a block model procedure, finding five equivalence classes, or blocks. To help characterize the roles these different blocks play in the network, we used the HITS algorithm to calculate hub and authority scores for each university [61] and examined these scores in relation to block membership (Fig. 2).

The first block includes ten prestigious, research-focused institutions with extremely high hub and authority scores (Fig. 2—yellow). These include the Massachusetts Institute of Technology (MIT), Harvard University, California Institute of Technology, Princeton University, University of California—Berkeley, Stanford University, University of Chicago, Cornell University, Yale University, and University of Illinois at Urbana-Champaign. It is noteworthy that MIT and Harvard are outliers in terms of their high hub scores. The second block (Fig. 2—orange)—mostly contains large research-intensive universities best characterized by having higher authority scores compared to universities in the remaining three blocks. One of the remaining blocks includes non-U.S. institutions (Fig. 2—dark blue), which have a large range of hub scores and, by definition, all have authority scores of 0 because no data were collected on the faculty they hire. Universities in the remaining two blocks have low hub scores but are distinguished by a slightly higher authority in one block (Fig. 2—light blue) compared to the other (Fig. 2—red). As described below, universities in the block with the lowest authority scores tend to be positioned on the periphery of the network (Figs. 3 and 4). Given these observations, we adopt the following monikers for each of these blocks, respectively: elites (yellow), high authority (orange), non-U.S. (dark blue), low authority (light blue), and periphery (red).

As part of assessing the adequacy of this block model, we examined a six-block model and noted that the additional sixth block contained only a single university, Massachusetts Institute of Technology. This suggests that no additional shared equivalence classes are identified by expanding the block model beyond five blocks. However, this result corroborates the overall importance of MIT in the network indicated by the HITs results.

C. Characterizing the universities in each block

Given that blocks were partitioned solely on the network structure, it is noteworthy that universities within each block are distinguishable by shared characteristics (Table I). Schools in the elite core blocks have the lowest average admission rates, the largest number of faculty in their department, and are universities with the largest research budgets. Admission rates increase and the other two variables decrease when moving toward the periphery schools. The ability to distinguish each block by varying characteristics helps to validate the use of a five-block model. Additionally, these characteristics are important in considering the types of cultural influence that propagate across this network.

D. Examining the network structure

The network resembles a core-periphery structure more typical of a layered core-periphery model, as opposed to a hub-and-spoke model (Figs. 3 and 4) [67]. The layered nature of this network is indicated by a general pattern of the highest density occurring among universities in the core of the network, with decreasing density toward the periphery. This indicates a nested hierarchy, where faculty are likely to find themselves working at a university that is either at the same position relative to the core as their undergraduate university or that is further away from the core than their undergraduate university. The sum of all non-U.S. institutions creates a second core within this core-periphery structure, having ties to nearly all universities other than those in the periphery block (Fig. 3). Notably, these patterns are similar in hiring networks from graduate school to faculty positions [12], highlighting the consistency of a hierarchical prestige network across the entirety of academic training.

E. Flow of faculty between blocks

By quantifying the total number of faculty in each possible block pairing (e.g., elites to high authority), we determined the proportion of faculty in each block that

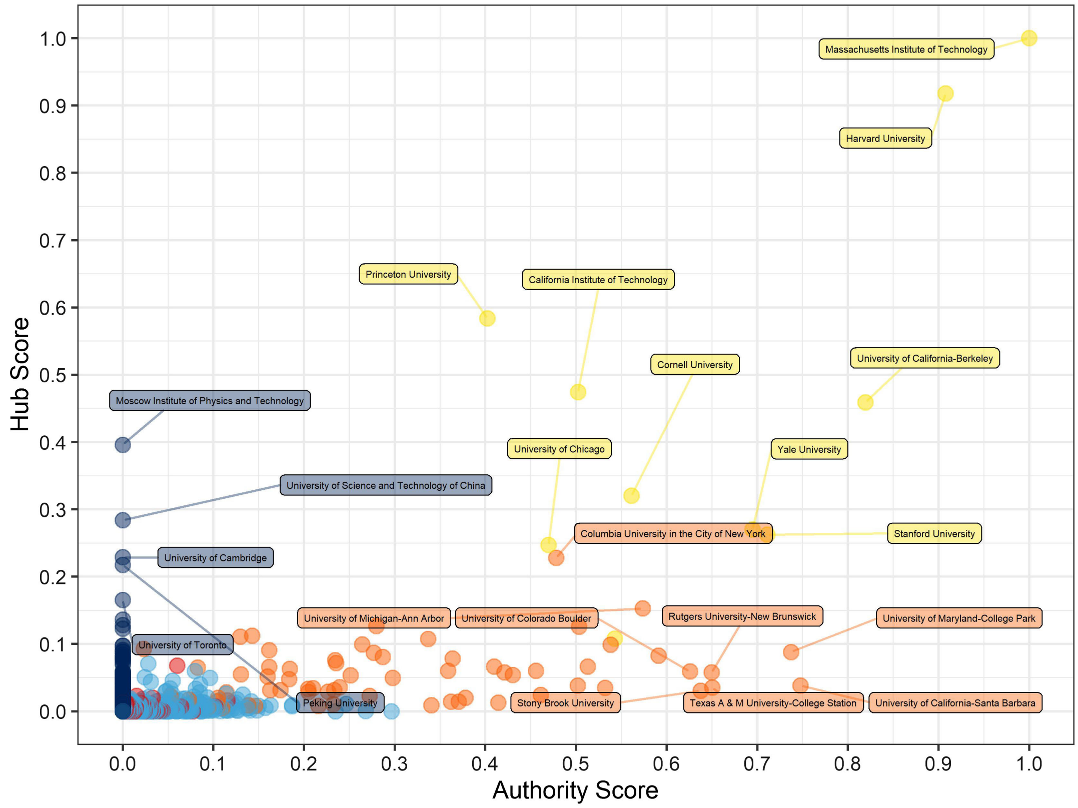

FIG. 2. Universities plotted by their hub and authority scores with color indicating block membership. Universities with high hub scores are those who have provided undergraduate training to a larger number of faculty with more of those faculty tending to work at universities with high authority scores. Universities with high authority scores tend to have faculty who earned their undergraduate degrees at universities with high hub scores.

FIG. 3. The block model image matrix indicates a layered core-periphery network structure with non-U.S. institutions taking on the role of a second core. Each cell represents the density of directed edges from universities in row blocks to universities in column blocks. For example, there are 660 possible directed edges that flow from the 10 elite universities to the 66 high authority universities, and 49.4% of these occur in our network.

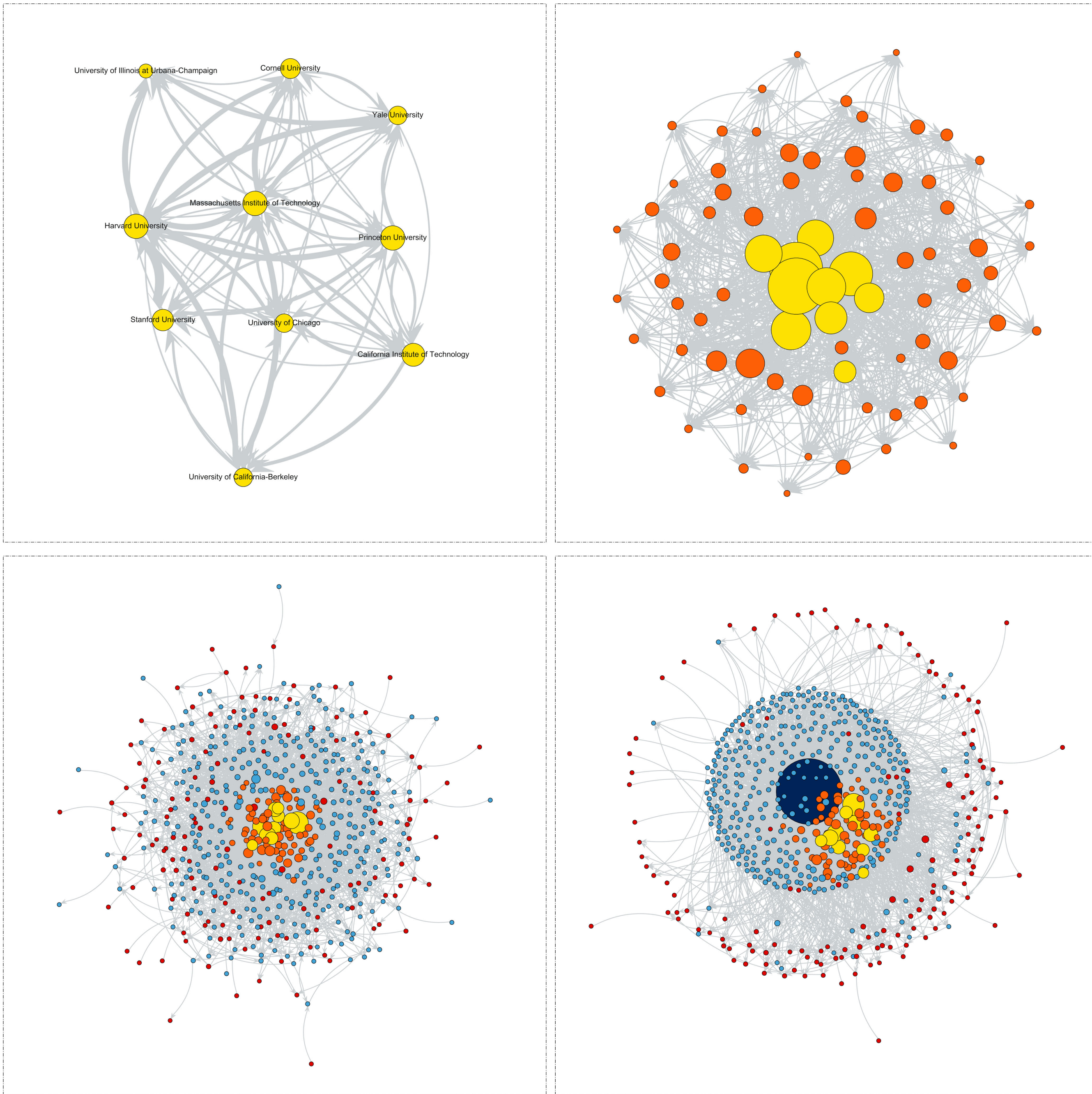

FIG. 4. The network structure illustrated by a series of sociographs that layer on additional universities by block membership from core to periphery. The network structure highlights a nested core-periphery structure. The size of each node correlates with the number of former undergraduates who are currently tenured or tenure-track physics faculty at U.S. institutions included in the network. Yellow nodes belong to the elites block; orange nodes belong to the high authority block; light blue nodes belong to the low authority block; red nodes belong to the periphery block; the dark blue node belongs to the non-U.S. block and represents 669 different non-U.S. institutions treated as a single node. Edge thickness corresponds with the number of undergraduates hired.

earned their undergraduate degree from each other block (Fig. 5). In each of the first four blocks, approximately 40% of faculty earned their undergraduate degree outside of the United States, with fewer faculty in periphery block schools having earned their undergraduate degree at a non-U.S. university. Despite being outside of the core of the network, universities in the high authority block provided undergraduate training for roughly 15% to 20% of faculty in each block. In contrast, the relative influence of undergraduate universities in the low authority block strengthens as you move from the core of the network toward the periphery.

TABLE I. Metadata (from 2017 to 2018 IPEDS [59]) about the universities that clustered into each of the six blocks. *Analyses treated all 669 non-U.S. alma mater institutions as a single university. Metadata about these non-U.S. institutions were not collected.

Block	Total schools	Department size	Number of undergraduates (SE)	Undergraduate admission rate (SE)	Mean research budget (USD)
Elites	10	51.9	21 296 (4,699)	13.9% (5.48)	718, 193, 452
High authority	66	37.3	29 552 (1,874)	43.9% (3.04)	448, 679, 265
Low quthority	389	9.7	12 186 (561)	64.7% (1.01)	38, 319, 928
Periphery	146	3.3	5537 (875)	65.4% (1.66)	6, 688, 547
Non-U.S.	1 (669)*	...	...	...	...

F. Elite institutions are the biggest levers

The block model procedures only account for whether university *j* employs at least one faculty from university *i*. However, many universities employ several faculty who earned their undergraduate degrees from the same university. Thus, identifying the biggest levers for change requires quantifying the total flow of faculty from undergraduate training to employer universities. Because single departments are often considered the key operational unit for change [68,69], we calculated the average number of undergraduate alumni per university within each block that currently work as faculty at a university within that same block or at a university in a different block (Table II).

Universities in the elite block average the greatest number of undergraduate alumni working as physics faculty in each other block and thus represent the biggest levers for every block. In each of these cases, universities in the high authority block are the second most productive universities. However, the margin of difference between these two is sizable. For example, on average, elite universities produced 12.4 times more alumni who are now faculty at an elite university compared to high authority universities. Similarly, compared to high authority universities, elite universities have graduated 6.7, 3.3, and 3.4 times more alumni who are now faculty within high authority, low authority, and periphery block universities, respectively. These margins are considerably larger when considering the low average number of alumni in other blocks who now work as faculty. The overrepresentation of undergraduate alumni from elite universities at other types of institutions is particularly noteworthy considering the institutional characteristics in Table I showing that these universities have smaller and more selective undergraduate populations than high authority institutions.

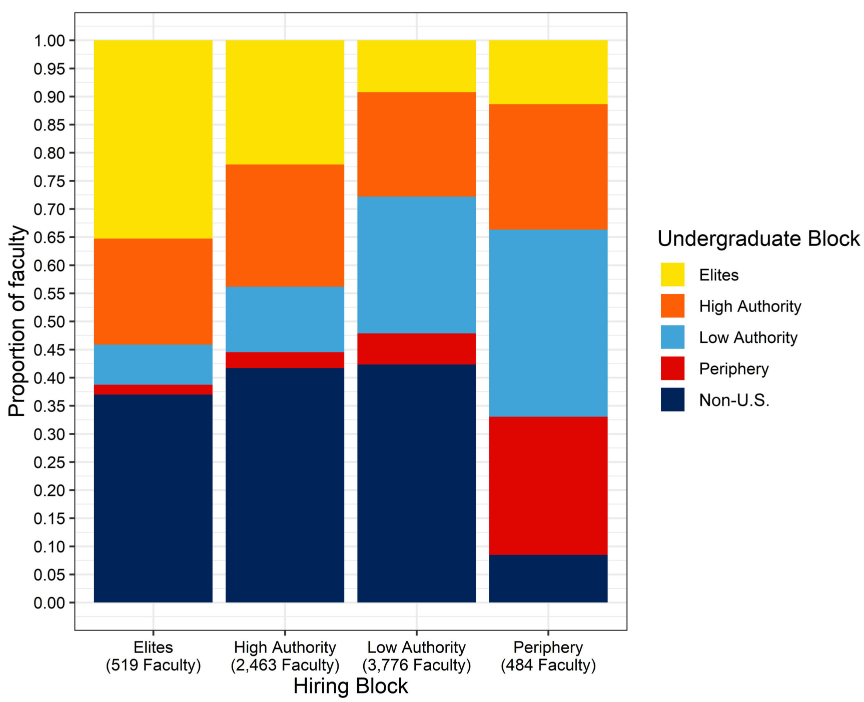

FIG. 5. Percent of faculty working at universities within each block by where they earned their undergraduate degree.

TABLE II. Average number of undergraduate alumni per school in each row block who now work at universities in each column block.

		Block of employer institution			
		Elites	High authority	Low authority	Periphery
Block of undergraduate institution	Elite (10 schools)	18.3	54.4	34.9	5.5
	High authority (66 schools)	1.48	8.12	10.62	1.64
	Low authority (389 schools)	0.10	0.74	2.36	0.41
	Periphery (146 schools)	0.06	0.48	1.43	0.82
	Non-U.S. (669 schools)	0.29	1.54	2.39	0.06

G. Slightly less than half of tenured and tenure-track physics faculty in the United States earned their undergraduate degree from a non-U.S. institution

Around 40% of tenured and tenure-track physics faculty in the United States earned their undergraduate degree from a non-U.S. institution. Though U.S. physics faculty represent 669 different non-U.S. alma maters, there is an imbalance in the countries where these degrees come from (Fig. S4 in the Supplemental Material [70]) and in the influence exerted among these universities. Ranking universities by the number of undergraduate alumni that are currently faculty across the 611 U.S. physics departments shows that 35 out of the top 100 universities are located outside of the United States (Supplemental Material [70]). Further, alumni from these 35 non-U.S. institutions are disproportionately found at elite institutions. In fact, 18.9% of faculty across the 10 schools in the elite block earned their undergraduate degrees at one of these 35 non-U.S. institutions.

IV. SUMMARY AND DISCUSSION

This paper provides a description of where physics faculty in the United States are trained at the undergraduate level. Our results reveal that a small fraction of institutions is responsible for the undergraduate education of a disproportionate number of U.S. physics faculty. The interinstitutional network's structure follows a prestige hierarchy, mirroring previous findings on the institutions where faculty earned their Ph.D. degrees [11,12]. Thus, the importance of institutional prestige in securing a tenure-track position in physics extends throughout the entirety of academic training, including undergraduate alma maters. We also found that more than 40% of all tenured and tenure-track physics faculty in the United States earned their undergraduate degrees from non-U.S. universities. A smaller number of these non-U.S. institutions are especially productive in training future physics faculty. Further, while the overall structure of the network indicates a prestige hierarchy, there were also universities in the low authority and periphery blocks that were isolated from the elite institutions in the core.

A. Heightened importance of a small set of institutions for reform

The overarching prestige hierarchy reflects the heightened influence of elite institutions' physics programs on the larger system. This suggests that the undergraduate admissions criteria and ability to retain students at these departments have an outsized impact on who becomes a physics professor. Similarly, the socialization experiences at these departments have an outsized impact on the cultural beliefs, attitudes, and values that these professors hold. This is consistent with patterns of institutional isomorphism, where universities undergo homogenization and become more like prestigious institutions [33,34,71].

The trend toward homogenization among universities can be problematic [33,34]. Most universities have teaching-focused missions, but when hiring, they draw from a pool of applicants whose training prioritized research, but would almost certainly benefit if pedagogical training was more important [21,72]. This discordance also leads to personal conflicts for faculty who graduated from research-focused institutions and now work in positions with a greater emphasis on teaching [73].

While rewiring the professionalization network to be more egalitarian would reduce the influence of elite institutions, the strength of the academic pipelines underlying the observed hierarchy renders this strategy impractical. Instead, the hierarchical nature of the observed network offers leverage to drive sustainable change. The undergraduate professionalization network presented here, along with previously published patterns indicating where faculty earn their Ph.D. [11,12], provides maps that can guide broad-scale implementation strategies for reform. However, rather than guiding the implementation of reform within a single department or university, this map offers guidance on how enacted reforms can contribute to broader change. Strategically focusing on institutions that produce the largest number of future faculty offers leverage to promote cost-effective downstream reform in higher education that may be essential to catalyze transformative change across the broader higher education system. Considering the other direction, it may not be possible to promote scalable change without addressing those institutions.

The idea of leveraging prestige structures in academia for change is not new. One initiative that employs this strategy is the Association of American Universities' (AAU) Undergraduate STEM initiative [74], which strategically implements research-based teaching practices across the 62 elite universities in North America that comprise the AAU. In a longitudinal study of this initiative, Kezar and Bernstein-Sierra identified influential pressures experienced by both core AAU institutions and institutions affiliated with core AAU institutions. Through interviews, observations, and document analysis, they identified that the prestige of the AAU institutions played a significant role in this influence.

The influence documented in the AAU STEM initiative differs mechanistically from the suggested impact exerted through faculty production. The influence of the AAU initiative was mimetic, as institutions chose to follow prestigious institutions in their decision-making process. This contrasts with the way influence operates through faculty production, which is slower and relies on the socialization of future faculty. Thus, we should expect the types of reforms capable of generating downstream impacts through faculty production to differ from those that work through the more mimetic mechanisms observed in the AAU Initiative. For example, if faculty "teach the way they were taught," as commonly stated [55], then it may be possible to advance pedagogical reform by focusing on reformed teaching practices that prioritize the experiences of students at elite institutions. However, the influence past undergraduate experiences have on teaching decisions is complex [52], which raises important questions. For example, is exposure to a single classroom taught using RBIS sufficient to prepare a future faculty to adopt similar methods, or even prime them to pursue similar methods, or is there a larger threshold of exposure required to establish these practices as normative [75]? Further, is a simple exposure to RBIS sufficient, or do prospective faculty have to have a positive attitude about the RBIS before they enact it, which is not always the case [76].

Leveraging the prestige hierarchy to promote greater diversity in physics may be a bit more straightforward. This is because it is tied more directly to the sequence of selection events, like admissions and hiring. Therefore, efforts to reform admissions practices at prestigious universities that may discriminate against prospective students from marginalized groups in physics represent an important step. However, these efforts may be insufficient without additional support and broader cultural changes [77,78].

We note that undergraduate experiences may seem like an unusual leverage point to drive reform. First, there is a very low probability that any given undergraduate will go on to become faculty, which makes graduate studies [79] and postdoctoral experiences [80] more obvious targets for reform. Second, undergraduate experiences are temporally distant from faculty positions, so any benefits from leveraging these experiences to bring about change would take a while to materialize. However, leveraging broader reform by focusing on reforming undergraduate experiences already aligns with ongoing national calls for higher education reform, particularly in teaching [14] diversity [81,82]. Thus, this strategy does not propose major changes to current initiatives; it simply emphasizes the importance of the larger system in which these ongoing initiatives take place.

B. Non-U.S. and insular institutions as special cases

Other important patterns existed within the observed network, including the high number of physics faculty who received their undergraduate training at non-U.S. institutions, reflecting the increasingly globalized higher education market [83–85]. Stakeholders engaged in improving higher education in the United States often overlook or ignore the prominence of institutions outside of the national system they aim to change. However, our data clarify that achieving sustainable change will require acknowledging the global nature of academia, including an understanding of how faculty incorporate international academic training into their current job contexts.

We also found many universities in the low authority and periphery blocks with minimal connectivity to the core. As a result, the academic cultures of these more insulated departments may experience a more isolated evolutionary trajectory compared to departments with more direct and indirect reliance on graduates from elite and high authority universities. Special cases of this phenomenon are physics departments in the low authority and periphery blocks that tend to hire their own alumni, which appeared to be more common among institutions with religious and military affiliations.

C. Other considerations

While our discussion has primarily focused on the importance of elite institutions for reform, we note that reform at these institutions may be more difficult to achieve compared to institutions located closer to the periphery for several reasons. The research-focused mission of elite institutions makes it challenging to implement teaching reform, while the high standards for admission at these institutions can complicate efforts to reform admissions criteria [77]. Further, the position of these institutions in the interinstitutional network makes them particularly prone to the influence of other core elite institutions. However, even if reform efforts at these institutions are especially costly or difficult, the sheer prevalence of future faculty who will have experienced undergraduate classrooms at these institutions suggests that systemic change may be particularly difficult without their involvement. It is also important to note that these institutions may have already implemented reforms to promote change, like the AAU STEM initiative [74] or the origination of peer instruction at Harvard [86].

These results should not be taken to negate the importance of reform at institutions that are outside of the networks' core. Reforming any institution has direct and immediate impacts on students, most of whom are enrolled at institutions outside the core of the network. Further, while institutions in the core produce a disproportionate number of faculty, the majority of physics faculty do not come from these institutions, and most universities do not directly hire faculty who were trained at these institutions. For example, only about 10% of faculty employed at universities in the low authority or periphery blocks earned their undergraduate degrees from elite institutions.

D. Limitations

Our study has certain limitations. First, it is limited in its focus on a single discipline. However, consistent cross-disciplinary results found in hiring networks [12] suggest that the overall structure of the physics professionalization network would likely be replicated across other disciplines. It is less clear whether other disciplines will have a similar number of faculty whose training occurred outside of the United States.

This study only focuses on tenured and tenure-track faculty members, even though individuals in non-tenure-track positions are indispensable for many aspects of undergraduate academic culture, especially in teaching [87]. However, inconsistent information on departmental websites made information about nontenured faculty or staff unreliable. We did not collect data from any two-year community colleges for similar reasons.

We did not collect information about the 669 non-U.S. universities in our dataset, including where faculty at these institutions earned their undergraduate degrees. This information is beyond the scope of our study which focused on U.S. institutions. However, the absence of these data directly and indirectly affected the calculation of hub and authority scores for U.S. universities in our dataset. The hub scores are likely to be underestimated for any U.S. university that has former students who are currently faculty at non-U.S. universities. This, in turn, would indirectly affect the authority scores of other U.S. universities that employ alumni from that institution. Thus, the estimated hub and authority scores can be considered semiglobal, as we only account for international connections in one direction. Similarly, we anticipate that the block model clusters would change if data were collected from both U.S. and non-U.S. universities. However, this more comprehensive collection and analysis of the global academic landscape is beyond the focus of the current work.

Finally, it is important to consider the role that department size played in our analyses. Larger departments naturally have more connections to other departments. As a result, department size was influential in our analyses, including hub and authority scores as their department placements in the block model. Despite this, we note that the sensitivity of our analyses to department size does not detract from the validity or applicability of our findings. Our study was focused on understanding interinstitutional influences in aggregate. Thus, in our analyses, we opted not to control for department size, and instead allowed it to intrinsically influence our findings, just as it influences the actual dynamics within the larger system of faculty production.

E. Conclusions

We collected and analyzed data on institutions where 7748 tenured and tenure-track physics faculty obtained their undergraduate degrees to understand the structure of faculty professionalization networks. Our findings align with previous research on the role of prestige in faculty hiring networks from doctoral programs [11,12], and expand our understanding of these networks by highlighting the similarly important role of the prestige of one's undergraduate alma mater. Given the importance of undergraduate institutions and the influential role that a small number of prestigious institutions play in the physics faculty hiring network, this study suggests that the most impactful strategies for transforming academic culture may lie in concentrating on the undergraduate experiences at these select elite institutions, which produce a disproportionate number of physics faculty across all types of institutions.

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APPENDIX A: DATA COLLECTION

Several challenges arose during data collection. In some instances, universities lacked physics departments and instead had tenured or tenure-track faculty on the roster who were responsible for teaching physics courses as part of a separate or more general science department. In these instances, we included data from these faculty. Other challenges came up that were specific to faculty with degrees from non-U.S. institutions. In many cases, faculty who attended non-U.S. universities did not earn a Bachelor of Science (BS) or Bachelor of Arts (BS) degrees, which are typical within the U.S. education system. Instead, these faculty earned degrees that were roughly equivalent to a typical BA or BS. In these instances, we treated the degree-granting institution as their undergraduate university. Historic changes to university names and national sovereignty led to many faculty listing university names or countries that are no longer recognized. This was particularly common among faculty who earned their degree in the former Soviet Union. In these instances, we listed these universities by their currently recognized names and as part of the sovereign state where they currently reside.

A unique situation involved the Claremont Colleges (Claremont McKenna College, Pitzer College, and Scripps College) sharing some of the same science faculty. Given our focus on interinstitutional influences, we treated each of these universities as distinct from the others. Thus, some physics faculty were duplicated in the dataset if they were listed on more than one institution's departmental web page. This decision was made to capture the influence of these faculty's past training on any future faculty who may be instructed by these faculty at any of the institutions in which they serve as faculty.

APPENDIX B: PATTERNS OF SELF-HIRING

In some cases, faculty were hired by the same university where they earned their undergraduate degree. In total, 4.2% of faculty in our dataset (306 total faculty) are employed as tenured or tenure-track faculty by their undergraduate alma mater. The tendency for universities to hire their own alumni varied by university type as well as where they were found in the professionalization network (Table III). Hiring one's own alumni was most common among universities with religious or military affiliations in the periphery or low authority blocks. Similarly, universities in the elite block displayed an elevated rate of hiring their own alumni, though the reasons for the rate of self-hiring between these different types of institutions likely differ.

TABLE III. Number of tenured and tenure-track faculty hired by their alma mater stratified by institution block membership and whether that university is religiously affiliated, militarily affiliated, or has no religious or military affiliation.

	Religious	Military	No affiliation
Elites	Not applicable	Not applicable	41/519 (7.9%)
High authority	2/101 (2.0%)	4/123 (3.3%)	51/2239 (2.3%)
Low authority	53/459 (11.5%)	15/100 (15.0%)	92/3217 (2.9%)
Periphery	32/229 (14.0%)	Not applicable	16/250 (6.4%)

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