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Trends in Ph.D. Productivity and Diversity in Top-50 U.S. Chemistry Departments: An Institutional Analysis

Sandra L. Laursen*,† and Timothy J. Weston‡

†Ethnography and Evaluation Research, University of Colorado Boulder, Boulder, Colorado 80309-0580, United States

‡ATLAS Assessment and Research Center, University of Colorado Boulder, Boulder, Colorado 80309-0320, United States

ABSTRACT: The education of doctoral chemists contributes to the chemical research enterprise and thus to innovation as an engine of the economy. This quantitative analysis describes trends in the production and diversity of chemistry Ph.D. degrees in the top-50 U.S. Ph.D.-granting departments in the past two decades. Time series data for individual departments from the Integrated Postsecondary Educational Data System are compared with aggregate data from the National Science Foundation. The results highlight departments that stand out from their peers in educating a diverse group of Ph.D. chemists. Best practices for diversity in doctoral education in chemistry are recommended.

KEYWORDS: *Graduate Education/Research, Chemical Education Research, Women in Chemistry, Minorities in Chemistry*

FEATURE: Chemical Education Research

A recent report on graduate education from the American Chemical Society asserts, "A vital program of graduate education in the chemical sciences is essential to assure the continued success of the enterprise and to sustain our nation in an ever more technical and globalized world" (ref 1, p 1). The quality and quantity of Ph.D. chemists is an important indicator of the health of the chemical research enterprise,[2] which in turn "powers the U.S. innovation engine".[3] Indeed, more than one-quarter of the jobs in the U.S. depend on chemistry in some way.[4] Yet concerns are widespread about the supply of Ph.D.-trained chemists, owing to retirement of the baby boomers and a continuing decline in the number of U.S. students pursuing doctoral study.[2,5]

The diversity of the Ph.D.-trained workforce is also of concern. A workforce that is not representative of society is wasteful and inefficient, failing to exploit the full range of talent available in the population.[5] It is also unjust, denying some groups equal access to the greater prestige, income, and job security offered by STEM jobs. Moreover, diverse work groups have been shown to outperform high-ability but homogeneous teams,[6] and businesses with a diverse workforce outperform less diverse competitors.[7] The economy needs scientists and innovators who can work effectively with diverse collaborators and respond to the needs of diverse consumers in an increasingly global marketplace,[8] skills learned as students pursue a degree in a diverse setting.[9−11]

In the present report, we examine doctoral education in chemistry from a quantitative perspective, analyzing public data to extract time-based trends in the production and diversity of Ph.D.s at the departmental level. Departmental trends are compared with national trends from aggregated data to identify individual departments that stand out in the representation of women and minorities among their doctoral graduates, or in the rate of growth in women's and minority representation over time. Most prior studies have examined single time points, often using aggregated data at a national level. This study is focused on individual departments, where specific local conditions and cultures can shape an environment that is effective—or not—in attracting, retaining, and supporting students from diverse backgrounds. The research questions address the nature and origins of these trends:

1. How do demographic trends in chemistry Ph.D.s awarded by individual departments compare to each other and to national aggregate trends?
2. What factors may explain observed differences in department-level patterns of educating Ph.D. chemists who are women or underrepresented minorities?

The analysis relates departmental data on Ph.D.s awarded to women and underrepresented minorities to available quantitative data on other departmental features, such as department size and faculty composition. Then, drawing as well upon the literature and upon qualitative data from a prior interview study of departmental perspectives on the challenges and opportunities in graduate education,[12] we suggest explanations for some of these demographic trends and offer examples of departmental practices that are effective in ensuring a productive and diverse pool of graduates.

■ PREVIOUS STUDIES OF GRADUATE EDUCATION IN CHEMISTRY

In recent years, about 2400 Ph.D.s in chemistry have been awarded per year.[13,14] This accounts for about 7% of all Ph.D.s in science and engineering, and 60% of doctorates in physical science. Recent scholarly work has focused on the persistent problem of underrepresentation of women and minority groups in chemistry and other STEM fields, and potential explanations and remedies for this disparity.

Relatively little work has been done on the "supply side" of doctoral education, examining students' choice to pursue a Ph.D. or enrollment in programs, and good data on graduate school entrance are hard to obtain.[15] Thus, it is unclear whether

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women, who are well represented at the bachelors level in chemistry, and minorities, who are not, enter graduate school at the same rate as men and majority students. Most studies agree, however, that while completion rates are higher in the physical sciences than in other fields, women's Ph.D. completion rates are lower than men's, and minority students' completion rates are lower than those for white students, which are in turn lower than those for international students.[15,16]

The reasons behind these lower completion rates have been explored in a number of studies. A literature review by Kuck and colleagues[17] showed that both men and women report dissatisfaction with their graduate training and career preparations, and problems in their working relationships with advisors and in their research groups; however, women are more dissatisfied with their experiences. Isolation can lead to loss of confidence and fewer opportunities to get help or develop collaborations. Gender differences affect the quality of advisor and peer relationships[18] and women experience a lack of fit with masculinized cultures that persist in many STEM disciplines.[19,20] Studies have also documented women graduate students' concerns about the career paths open to them, including lack of positive role models and the difficulties they anticipate in combining a research career with a family or personal life.[19−22] Together, these factors present a "glass obstacle course" of gendered barriers to women's success in STEM graduate programs.[19] These barriers were often invisible to women until they stumbled upon them, but could cause women to doubt their ability and desire to complete the doctoral degree, to continue in the field, or to pursue a faculty or other research position.

The underrepresentation of women and minorities among Ph.D. graduates has a strong effect on the diversity of faculty who will then teach and mentor the next generation. Because elite schools tend to hire faculty who are graduates of other elite schools,[23] the diversity of graduates from highly ranked schools is especially critical in this respect. Lack of representation of women on chemistry faculties is not solely due to a lack of diversity among those earning doctorates: more than men, women tend to lose interest in faculty positions during graduate school[24,25] and are less likely to apply for faculty positions.[26] Yet the proportion of new Ph.D.s who are women constrains the possibilities for gender balance of the faculty, and as noted above, factors that may lead to some women's attrition from doctoral programs are the same as those that may lead others to complete the degree but to pursue careers outside academe, or outside research altogether.[25]

While the literature focuses more strongly on women in academe, most Ph.D.-trained chemists work outside academe.[27] Indeed, chemistry graduate students are less attracted to academic careers than those in other disciplines.[28,29] A recent study in the U.K. found that during graduate school, women lost interest not only in academic research careers, but in any research career.[25] Data on women in the technical workforce outside academe are "virtually impossible" to come by,[30] but women are chronically underrepresented at the top executive level, at below 15% of positions in the top 42 public chemical firms.[31]

Among underrepresented minority (URM) groups, the drop-off from Ph.D. to faculty is even more stark.[32−34] Because the absolute numbers are so very small, it has been difficult to acquire good data on minority Ph.D. students that are disaggregated both by discipline and by ethnic group.[35] Aggregation may be helpful in identifying general issues, but does not reveal challenges and opportunities that may be specific to a discipline or to students from a particular cultural group. Nettles and Millett point to some troubling aspects of minority students' academic and socialization experiences in graduate school that result in lower research productivity than that of their white peers and therefore affect graduates' options. Ong and co-workers' synthesis of empirical research on women of color in STEM highlights the "double bind" that minority women experience.[36] Social barriers more than lack of academic ability or interest are the main disincentives to pursuit of higher STEM education. These include faculty perceptions that women of color are not serious students, difficult transitions to predominantly white institutions from the supportive environments of minority-serving institutions and community colleges where many of these women begin, and challenges in finding mentors and supportive peer groups. Other recent work suggests that developing an identity as a scientist is especially important for members of underrepresented groups.[37] With respect to minorities in industry, again data are difficult to come by, but some observers suggest that the paucity of URM chemists in academe conversely benefits diversity in industry.[8]

■ STUDY METHODS

The institutional sample is based on the "Top 50" chemistry doctoral programs, using a composite index developed by David Fraley.[38] While the choice of any single ranking system is problematic, we selected this one for its incorporation of multiple sources of external rankings across the time span of our data set. This index incorporates overall ratings from U.S. News in 2007[39] and the National Research Council's 1995 report, which includes factors ranking the "scholarly quality of the faculty" and the "program effectiveness in educating research scientists."[40] The NRC's most recent analysis of doctoral programs[41] provides, instead of a single rank, a ranking range that could not be used quantitatively. However, separate analyses verified that the set of 50 departments would differ little if central values of the NRC ranking ranges were considered. Together, these 50 departments account for some 60% of all chemistry Ph.D.s awarded each year. While data were available for other chemistry doctoral programs, adding these to the data set did not enhance the analysis, as clear departmental trends could not be discerned in small programs averaging fewer than about 10 Ph.D.s awarded per year, which was the case for most of the remaining programs. Results presented below show that the 50-school data set accurately reflects national trends.

Data on doctoral degrees awarded in chemistry by individual departments came from the Integrated Postsecondary Educational Data System (IPEDS) of the U.S. Department of Education.[42] Through its annual surveys of every college, university, and technical and vocational institution that participates in federal student financial aid programs, IPEDS provides a comprehensive view of degree completion and many other facets of higher education. From these public data, reported by institutions each year, we have compiled time series data on Ph.D.s awarded in chemistry, including all subfields gathered by IPEDS. The IPEDS data are resolved by gender since 1987 and by race/ethnicity and citizenship since 1995. This data set includes the years 1987−2009.

We obtained data on Ph.D.s awarded in chemistry for each institution and year from the IPEDS Data Center and compiled these into time series. These data are referred to as the "50-school" data. Aggregated, national data (without individual institutions) from the National Science Foundation[13,14] portray the total number of chemistry Ph.D., Masters and Bachelors (BA/BS) degrees granted from 1966 to 2008 (the "national" data).

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Comparison of the two data sets shows similar trends in overall Ph.D.s granted for the overlapping time period and confirms the 60% figure for departmental representation (Figure 1).

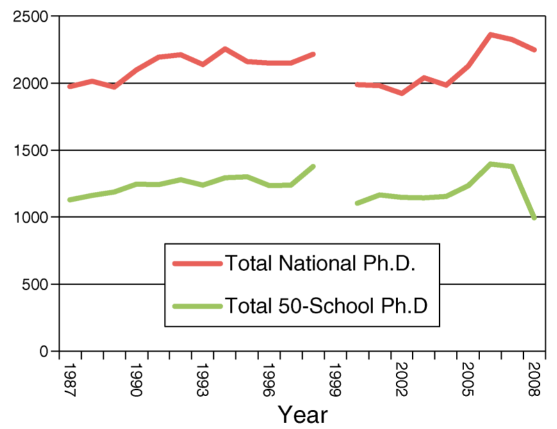

Figure 1. Comparison of national data and 50-school data: total Ph.D.s granted, by year (1987−1998, 2000−2008).

To compare the IPEDS Ph.D. data set with faculty data, we used the Nelson Diversity Surveys, which count the number of tenure-stream faculty from each racial/ethnic group, by gender, at each institution in the 50-school data set.[33] These departments ranged from 4 to 26% women, with a mean of 14% in this set of departments. They had from 0 to 25% faculty from under-represented groups, with a mean of 4% URM faculty.

While the focus of this analysis is quantitative analysis of the IPEDS data set, our interpretation also draws on a set of 22 interviews conducted with department chairs and graduate program directors at 14 chemistry doctoral programs also represented in the 50-school data set.[12] These interviews provided information on intellectual, social and demographic trends that these well-placed observers had noticed in their own departments or in the field more generally, on opportunities and challenges for their graduate programs, and on changes their department had made to its practices, especially those focused on the professional preparation of graduate students. These data, described in detail elsewhere,[12] enrich interpretation of the primary, quantitative data set. The interviews are not claimed to be representative of all 50 schools, nor do they reflect the perspectives of individual faculty and students; rather they are used to provide examples of departmental leaders' awareness of diversity issues and of department-level actions taken (or not).

Variables

The variables used in the study are presented in Table 1. Variables include absolute counts of total degrees for each year of the sample, four and five-year averages for the 2004−2008, 2004−2009 periods representing current representation of women and racial/ethnic groups, and percentages for each year for women and racial/ethnic groups. Ordinary Least Square (OLS) coefficients gained from regression models were used to estimate growth per year and over the sample period (see below). Overall, the analysis focuses on both representation of different groups among chemistry Ph.D.s awarded and growth over time in this representation.

Analysis Methods

We examined trends in women's and minority doctoral degrees in chemistry using Hierarchical Linear Models[43] (HLM) to test if growth in representation grew significantly over the years represented by the sample. We used HLM to test whether linear trends in representation were significant, and whether hypothesized relationships between the size of the institution, faculty representation of women and female student representation were statistically significant. We did not attempt to construct a comprehensive explanatory model of all possible factors predicting the dependent variable. HLM is used because of the nested structure of the data (years nested within institutions), and because variables such as *Percentage Women Faculty* are institutional (not annual) characteristics. Nested data is more appropriately treated in a model that accounts for all sources of variability. Moreover, the unconditional models showed intraclass coefficients indicating that 15% of total variance is attributable to institutional variability, making the use of multilevel modeling necessary to account for variation among institutions.[43]

The specific HLM model used for testing these hypotheses was a two-level random-intercept model representing years (i) nested within institutions (j),

$$\begin{aligned} Y_{ij} &= b_{0j} + b_{1j}\,(\mathrm{Year}_i) + r_{ij} \\ b_{0j} &= \lambda_{00} + \lambda_{01} W_j + \mu_{0j} \\ b_{1j} &= \lambda_{10} \end{aligned} \tag{1}$$

where first-level coefficients b_{1j} predict (in separate models) the dependent variables (Y_{ij}) *Percentage women* or *Percentage minority* for each institution and $Year_i$ is a first-level predictor. With the centered intercept values (b_{0j}) representing average representation for each school across years, the second-level predictors of representation (W_j) are characteristics of institutions such as *Total degrees granted, Percent women faculty* and *Percent minority faculty*. The error terms r_{ij} and μ_0 denote residual variability for level-1 and level-2 variables. The model tests whether the percentage of women or minorities granted doctorates significantly increases (or decreases) over years, taking into account variance among institutions, and whether the total degrees granted and the representation of women or minority faculty predict the average percent of women in departments over years. Coefficients in this part of the model can be interpreted as reflecting the average percentage of women or minority graduates' growth per year.

We also wanted to know if rates of growth among individual institutions were dependent upon factors such as the size of the institution and minority representation. For this test, we used a two-level random effects model predicting growth coefficients (b_{1j}),

$$\begin{aligned} Y_{ij} &= b_{0j} + b_{1j}\,(\mathrm{Year}_i) + r_{ij} \\ b_{1j} &= \lambda_{00} + \lambda_{01} W_j + \mu_{1j} \\ b_{0j} &= \lambda_{00} \end{aligned} \tag{2}$$

where first-level coefficients b_{1j} are growth rates across years for each institution (j) (represented by Ordinary Least Squares coefficients b_{1j}), $Year_i$ is a first-level predictor, and the second-level W_j are variables representing institutional characteristics of *Total degrees granted, Women faculty* and *Minority faculty* representation. This model tests if rates of growth at each institution can be predicted by the relative size of a department and overall women and minority representation in faculty. In the case of the growth model, coefficients for second-level

Table 1. Variables Used in This Analysis

Variable	Description	Scale
Average Total Degrees Granted (2005–2009)	Average per year of chemistry Ph.D. degrees granted over five-year period.	Average number of degrees
Average Total Degrees Granted	Average total number of degrees granted at each institution over entire period (1987–2009,1995–2009)	Number of degrees
Growth in Degrees Granted	Growth in total number of chemistry Ph.D. degrees granted over grant period.	Number of degrees increase/decrease
Average Percent Women (2005–2008)	Average percentage over four years in Ph.D. degrees granted to women (2005–2008)	0–100%
Average Percent Women (1987–2008)	Average percentage over all years in Ph.D. degrees granted to women (1987–2008)	0–100%
Percentage Women (1987–2008)	Percentage per year of Ph.D. degrees granted to women (1987–2008)	0–100%
Average Percent White, African-American, Hispanic, Asian, Non-Resident (2004–2009) (Racial/Ethnic)	Average percentage over five years for Ph.D. degrees granted to each racial/ethnic group (2005–2009). Degrees to students of unknown racial ethnicity removed from denominator for percentage.	0–100%
Average Percent White, African-American, Hispanic, Asian, Non-Resident (1995–2009)	Percentage per year of Ph.D. degrees granted to each racial/ethnic group (1995–2009). Degrees to students of unknown racial ethnicity removed from denominator for percentage.	0–100%
Percent Underrepresented Minority (URM) (2005–2009)	Summed average percentage of African-American + Hispanic + Native American granted Ph.D. degrees over five-year period.	0–100%
Percent Underrepresented Minority (URM) (1995–2009)	Percentage per year of Ph.D. degrees granted to URMs (1995–2009)	0–100%
Percent Growth Women (1987–2008)	Increment per year predicted in percentage from OLS coefficient.	OLS coefficient
Percent Growth Racial/Ethnic (1995–2009)	Increment per year predicted in percentage from OLS coefficient	OLS coefficient
Percent Women Faculty	Percentage of women faculty at each institution	0–100%
Percent Minority Faculty	Percentage of faculty in each racial ethnic group at each institution in 2007	0–100%

independent variables such as *Percentage women faculty* can be interpreted as the change in the growth coefficient associated with one unit of percentage for faculty representation.

For models predicting trends for race/ethnicity, "dummy" or dichotomous variables for each group (e.g., White = 1, Other = 0) were used in the analysis. We followed best practice in this analysis to avoid collinearity by including a reference variable (unknown ethnicity) that was left out of the analysis when testing racial/ethnic categories in our models.[44] We also checked collinearity statistics to ensure that analyses were not affected by this condition.

Total growth for women and for minorities over all years was calculated through the OLS regression coefficients (b_{1j}) for each institution from the growth model with year predicting *Percentage women* over the 22 years of the sample, and similarly for minority students for the 14-year sample:

$$(\%\text{ gain women} = 22\text{ years} \times b_{1j}) \quad (3)$$

$$(\%\text{ gain minority} = 14\text{ years} \times b_{1j}) \quad (4)$$

■ RESULTS

We present results for total doctorates, then those awarded to women, followed by minorities and international students, for which the IPEDS database uses the term nonresident alien.

Total Doctorates

This analysis examines both descriptive data and time series data for all students in chemistry Ph.D. programs. Table 2 shows the results by department for total doctorates, growth in degrees granted, and the rank of each institution in size and growth. Institutions are listed by rank in average number of degrees granted.

Figure 2 shows the trends in absolute numbers from the NSF database of chemistry degrees awarded per year, which indicate almost no growth in total chemistry doctorates or masters degrees granted since 1966. The number of bachelor's degrees has fluctuated substantially over the years, but has shown little overall total growth. In the 50-school data set, the average number of doctorates awarded by each school (five-year average, 2005–09) is 25 and the average growth rate is two degrees over the entire 22-year sample period.

While aggregate growth is small, it masks a large range of increases and decreases in total Ph.D.s granted by individual departments. Of the 50 departments, 29 showed a positive growth trend and 18 a negative trend; two schools showed no net change. Over the 22-year period, six departments grew by 10–20 Ph.D.s, and four shrank by over 10 Ph.D.s.

We found only weak correlates to the magnitude of departmental growth; while there is a small negative correlation between the average size of a department over time (on one hand) and growth, this relationship was not statistically significant. It is possible that more departments showing a net long-term shrinkage exist but are outside the Top-50 data set; however, the overall trend in growth is consonant with growth from all schools in the national data.

Women's Representation

The percentage of women receiving Ph.D.s grew substantially over the past 50 years. Figure 3 shows the increase, from national data, in the representation of women receiving chemistry degrees at all levels from 1966 to 2008. While a smaller proportion of women receive Ph.D.s than Masters or Bachelors degrees, the rate of increase for women who received

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Table 2. Total Chemistry Ph.D. Degrees Granted and Growth in Degrees Granted

Institution	Average Number of Degrees per Year (2005−2009)	Rank in Degrees Granted	Growth in Number of Degrees Granted (1987−2009)	Rank in Growth, Degrees Granted (1987−2009)
University of California—Berkeley	65.2	1	0	31
Purdue University—Main Campus	46.0	2	3	20
University of Florida	43.3	3	18	3
Massachusetts Institute of Technology	42.0	4	−3	38
University of Illinois at Urbana—Champaign	39.6	5	−4	42
University of Michigan—Ann Arbor	39.0	6	6	13
University of Wisconsin—Madison	36.8	7	−11	48
University of North Carolina Chapel Hill	35.0	8	2	24
University of California—San Diego	35.0	8	10	6
Pennsylvania State University—Main Campus	34.8	10	1	28
Northwestern University	33.6	11	10	6
Texas A & M University	33.0	12	−6	46
University of Washington—Seattle Campus	32.7	13	12	4
California Institute of Technology	32.5	14	3	20
University of Minnesota—Twin Cities	32.2	15	2	24
Stanford University	31.8	16	4	18
The University of Texas at Austin	30.8	17	−2	34
Harvard University	30.5	18	8	10
University of California—Los Angeles	30.3	19	5	15
University of California—Irvine	29.7	20	20	2
Georgia Institute of Technology—Main Campus	29.0	21	21	1
University of Pennsylvania	28.8	22	9	8
Michigan State University	28.0	23	1	28
Cornell University	25.7	24	−3	38
University of California—Davis	24.7	25	11	5
Ohio State University—Main Campus	24.5	26	−14	49
University of Colorado Boulder	24.3	27	−1	33
Iowa State University	24.0	28	−14	49
University of Chicago	22.4	29	−2	34
Princeton University	22.3	30	2	24
Columbia University in the City of New York	21.3	31	0	31
University of Pittsburgh—Pittsburgh Campus	20.8	32	−2	34
University of Utah	20.8	32	1	28
University of Arizona	19.5	34	−2	34
Emory University	19.2	35	5	15
Yale University	19.0	36	−5	45
Louisiana State University and Agricultural & Mechanical College	19.0	36	7	11
University of California—Santa Barbara	18.5	38	5	15
University of Virginia—Main Campus	17.5	39	4	18
University of Southern California	17.3	40	−3	38
Duke University	16.3	41	3	20
University of Maryland−College Park	16.2	42	−3	38
Florida State University	15.8	43	9	8
Virginia Polytechnic Institute and State University	14.8	44	−4	42
Rice University	14.7	45	2	24
Indiana University—Bloomington	14.2	46	−10	47
Washington University in St Louis	14.0	47	6	13
Johns Hopkins University	13.8	48	3	20
Colorado State University	11.8	49	−4	42
University of California—San Francisco	—	—	7	11

Ph.D.s tracked the rates of change for those receiving Masters and BAs.

The national and 50-school data showed very similar trends from 1987 forward (see Figure 4). In the 50-school data set, the average percentage of women in the most recent five years (2005−2009) is 36% and the average growth rate of women is 14% over the 22-year period (1987−2009).

Analysis of overall patterns in growth reveals some interesting trends. Table 3 presents the regression model for percentage women in departments, with total size (degrees granted) and percentage women faculty in department.

HLM analysis shows that representation of women grew over the years in the study; Ph.D.s granted saw an average of 0.6% growth per year, with a total growth over 22 years of 14%.

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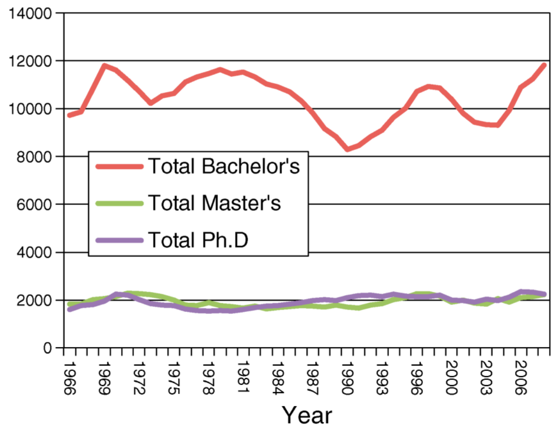

Figure 2. Total chemistry degrees granted (1966–2008).

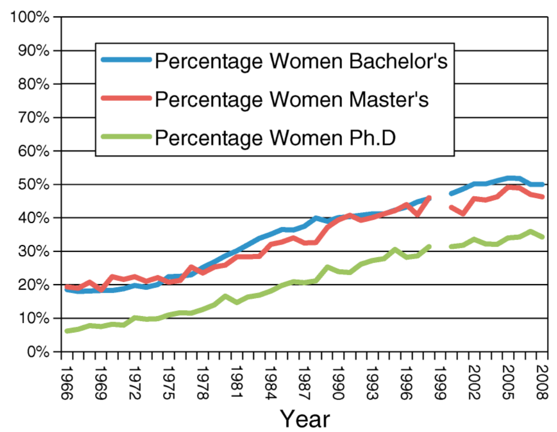

Figure 3. Percentage of women receiving chemistry degrees (1966–1998, 2000–2008), from national data.

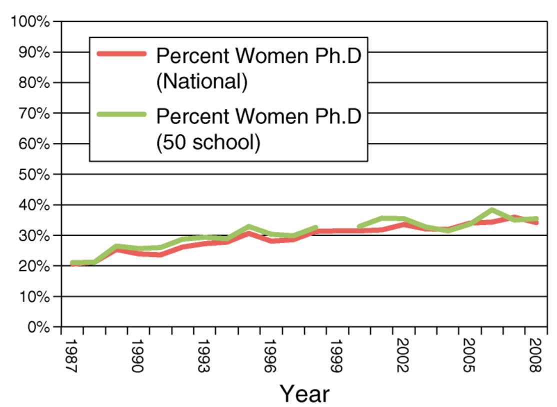

Figure 4. Percentage of women receiving chemistry Ph.D.s (1987–2008), from 50-school and national data.

Departments that grant more Ph.D.s (e.g., larger departments) grant relatively fewer Ph.D.s to women; that is, large departments are less gender-balanced. We see this with the effect for *Total Degrees Granted*; the effect is small with each degree given by departments corresponding to a decrease of 0.14 of a percent in *Average percent women*. However, in the second model, *growth* in overall doctorates correlates with *growth* in doctorates to women with a positive relationship.

We also wanted to know if the number of women faculty in a department predicted female doctorates' representation. We found an inverse statistical relationship between the *growth* of women Ph.D.s from a department and the percentage of women faculty, indicating that departments with greater number of women graduates had fewer women faculty. This inverse effect was small but significant with one additional percentage of women faculty corresponding to −0.015 of a unit of growth.

While the proportion of women among Ph.D. graduates is steadily growing on average, there is high disparity among departments: some institutions are graduating women at twice the national average, and some show a negative trend over time. Given these trends, it is interesting to examine which individual departments stand out from the average in terms of representation and growth. Table 4 presents the percentage of degrees granted to women and growth in degrees granted to women at institutions in the 50-school data set, listed in order of highest to lowest percent women.

For degrees granted to women (1987–2009), highly ranked (top 10 of 50) schools for percentage women among Ph.D. graduates include Louisiana State University, Michigan State, University of Washington, University of Florida, and Emory University, at values nearing 50% women. Three of these institutions are also positive outliers in their growth in women's representation over the period 1987–2009, including Washington, Florida, and Michigan State. In these departments, growth in the representation of women over time has yielded nearly gender-equitable graduating classes.

Some lower-ranked schools for percentage of degrees granted to women include Colorado State University, Ohio State University, Columbia University, University of Chicago, and Harvard. Of these, University of Chicago and Colorado State University also had low growth rates. Table 5 summarizes these distinctive departments that appear in the top or bottom five when ranked on both representation and growth. Only Johns Hopkins achieved above-average representation of women despite only low growth. Conversely, women's representation at University of California—Irvine is still low but is growing rapidly.

Minority Representation

The number of chemistry Ph.D.s granted to people from underrepresented minority groups is growing, but still very small, on the order of 5% of all chemistry Ph.D.s.

In the 50-school sample, the average percentage of chemistry Ph.D. degrees granted to minorities from 2005–2009 was small, with an average 2% representation for African-Americans and 3% for Hispanic students (Table 6). Students classified as Asian by IPEDS (that is, Asian-Americans) represented slightly more Ph.D.s granted, with 7% of total degrees. International students, termed nonresident aliens in IPEDS, had the highest representation with 37% of total degrees. Using the *Underrepresented Minority* (URM) classification for African-American, Hispanic, and Native American students as a group, the current numbers show an average of 5% of students in this group. While several schools had representation between 10–20% URM, the majority of schools had between 0–5% representation.

Overall, data from the national sample show that student bodies became only slightly more diverse from 1995 to 2009 (Figure 5). The proportions of U.S. white students fell 11%, mostly due to the influx of international students. Overall, the decrease in the proportion of white students was inversely related to total degrees granted, but total degrees granted did

Table 3. Regression Coefficients and Standard Errors for HLM Analysis: Representation and Growth of Women Receiving Chemistry Ph.D.s[a]

	Coefficient (Unstandardized)	Standard Error	T	Df	P
Level 1: Dependent Variable: Percentage Women (by year 1987–2008)					
Year	0.006	0.0005	12.1	1053	0.0001**
Level 2: Dependent Variable: Average Percent Women (1987–2008) (b_{0j})					
Total Degrees Granted	−0.0014	0.000 614	−2.2	48	0.03*
Percentage Women Faculty	−0.1336	0.1230	−1.087	48	0.283
Level 2: Dependent Variable: Percent Growth Women (1987–2008) (b_{1j})					
Total Degrees Granted	0.000 09	0.000 045	2.0	47	0.049*
Percentage Women Faculty	−0.015	0.007	−2.1	47	0.04*

[a]Variable *Average Percent Women* is represented by centered intercept term b_{0j} from eq 1. Variable *Percent Growth Women* is represented by OLS coefficients b_{1j} from eq 2. *Denotes significance at $\alpha < 0.05$ level. **Denotes significance at $\alpha < 0.01$.

Table 4. Representation and Growth in Ph.D. Degrees Granted to Women

Institutions in the 50-School Data Set	Ph.D. Degrees to Women (2005–2009), %	Rank in Percentage Women	Growth in Degrees Granted to Women (1987–2009), %	Rank in Percentage Growth in Women Students (1–50)
Louisiana State University and Agricultural & Mechanical College	49	1	23	7
University of Washington—Seattle Campus	47	2	30	1
Michigan State University	47	2	29	2
University of Florida	45	4	27	4
Emory University	44	5	10	34
Georgia Institute of Technology—Main Campus	41	6	20	10
Purdue University—Main Campus	40	7	15	24
University of North Carolina Chapel Hill	40	7	11	33
Johns Hopkins University	40	7	4	47
University of Michigan—Ann Arbor	39%	10	20	10
University of Arizona	39	10	17	18
Duke University	39	10	15	24
University of Virginia—Main Campus	38	13	13	29
University of Pennsylvania	38	13	7	39
University of California—San Diego	37	15	20	10
University of Colorado Boulder	37	15	18	16
Yale University	37	15	12	30
Pennsylvania State University—Main Campus	36	18	17	18
University of Maryland—College Park	36	18	7	39
University of Illinois at Urbana—Champaign	35	20	20	10
Cornell University	35	20	18	16
University of California—Berkeley	35	20	14	26
University of Minnesota—Twin Cities	35	20	14	26
University of California—Davis	35	20	5	43
University of Wisconsin—Madison	34	25	20	10
Stanford University	34	25	19	15
Northwestern University	34	25	17	18
The University of Texas at Austin	34	25	17	18
University of California—Los Angeles	34	25	5	43
Virginia Polytechnic Institute and State University	33	30	24	6
University of Utah	33	30	22	8
California Institute of Technology	33	30	14	26
University of Southern California	33	30	−6	50
University of Pittsburgh—Pittsburgh Campus	32	34	25	5
Massachusetts Institute of Technology	32	34	9	36
University of California—Irvine	31	36	29	2
Indiana University—Bloomington	31	36	16	23
Rice University	31	36	12	30
Texas A & M University	31	36	10	34
Princeton University	31	36	5	43
Florida State University	30	41	17	18
Iowa State University	30	41	8	38
University of California—Santa Barbara	30	41	3	48
Washington University in St. Louis	29	44	−3	49

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Table 4. continued

Institutions in the 50-School Data Set	Ph.D. Degrees to Women (2005–2009), %	Rank in Percentage Women	Growth in Degrees Granted to Women (1987–2009), %	Rank in Percentage Growth in Women Students (1–50)
Ohio State University—Main Campus	28	45	12	30
Colorado State University	28	45	6	42
Columbia University in the City of New York	27	47	9	36
University of Chicago	24	48	5	43
Harvard University	20	49	7	39
University of California—San Francisco	missing	missing	22	8

Table 5. Departments Distinctive in Representation and Growth of Ph.D. Degrees Awarded to Women

	High Growth (Ranked in Top 10 in Growth)	Low Growth (Ranked in Bottom 10 in Growth)
High representation (ranked in top 10 in representation)	University of Florida Michigan State University University of Washington	Johns Hopkins
Low representation (ranked in bottom 10 in representation)	—	University of California—Santa Barbara Washington University in St. Louis Colorado State University University of Chicago

Table 6. Percentages of Chemistry Ph.D.s Granted, by Racial/Ethnic Group (2005–2009)[a]

Racial/Ethnic Group	Mean
White	51%
African-American	2%
Hispanic	3%
Native American	>1%
Nonresident	37%
Asian	7%

[a]Totals reflect percentage of all students with those of unknown ethnicity removed.

not correlate with growth or shrinkage in particular departments.

Regression models (Table 7) show the representation of underrepresented minorities rose slightly from 1995 to 2009, with a growth rate of 1.6% over this 14-year period. Within this group, the only significant growth in the URM population occurred with Hispanic students where the proportion of Hispanics awarded Ph.D. degrees rose from 3% to 4.4% over the 14-year period. *Total Degrees Granted* also had a positive relationship with Hispanic representation. For the URM group,

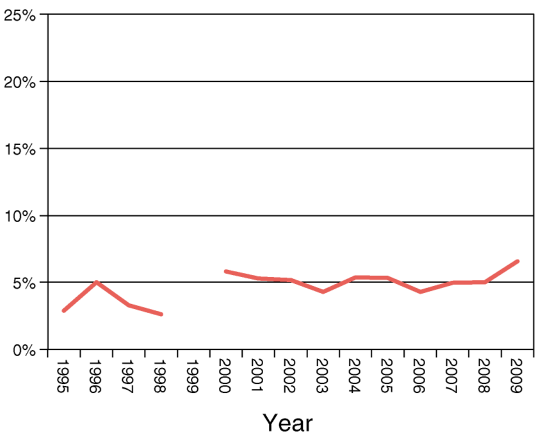

Figure 5. Average percentage of chemistry Ph.D. degrees granted to URM students (1995–1998, 2000–2009).

Table 7. Regression Coefficients and Standard Errors for HLM Analysis: Representation and Growth of URMs Receiving Chemistry Ph.D.s[a]

Variable	URM	Hispanic	White	International	Degrees of Freedom
	Dependent variable: Percent in Racial/Ethnic Group (by year 1995–2009)				
Level 1: Year	0.0014**	0.001**	−0.008**	0.0008**	657
	(0.00058)	(0.0003)	(0.0014)	(0.0015)	
	Level 2: Dependent Variable: Average Percent Racial/Ethnic (b_{0j})				
Total Degrees	−0.000 12	0.0004*	0.0039	0.002	48
	(0.0004)	(0.00019)	(0.0014)	(0.0015)	
Percent Minority Faculty	0.082*	0.167	−0.40	0.8	48
	(0.042)	(0.93)	(0.22)	(0.5)	
	Level 2: Dependent Variable: Percent Growth Racial/Ethnic (b_{1j})				
Total Degrees	0.000 052	0.000 035	0.000 16	−0.000 16	47
	(0.000072)	(0.00004)	(0.00014)	(0.00014)	
Percent Minority Faculty	0.001	0.006	0.025	0.004	47
	(0.006)	(0.005)	(0.02)	(0.02)	

[a]Variable *Average Percent Racial/Ethnic* is represented by centered intercept term b_{0j} from eq 1. Variable *Percent Growth Racial/Ethnic* is represented by OLS coefficients b_{1j} from eq 2. *Denotes significance at $\alpha < 0.05$ level. **Denotes significance at $\alpha < 0.01$. Unknown ethnicity used as reference variable in models to avoid collinearity. Hispanic and URM tested separately.

Table 8. Percentage and Growth in Ph.D. Degrees Granted, by Racial/Ethnic Group

	2005–2009								1995–2009	
Institution[a]	White, %	African-American, %	Hispanic, %	Native American, %	Nonresident, %	Asian, %	URM, %	Rank for URM	Growth URM, %	Rank for Growth URM
Louisiana State University and Agricultural & Mechanical College	25	19	1	0	53	2	20	1	11	3
Purdue University—Main Campus	36	6	10	1	45	3	17	2	22	1
University of California—San Diego	60	1	9	1	15	14	11	3	7	6
University of California—Los Angeles	52	1	9	0	19	19	10	4	9	4
Florida State University	49	7	2	0	38	4	9	5	16	2
University of California—Irvine	60	0	9	0	17	13	9	5	8	5
Harvard University	56	1	8	0	32	4	9	5	6	10
University of California—Santa Barbara	51	3	6	0	24	16	9	5	2	19
Texas A & M University	41	3	5	1	43	8	9	5	−7	47
University of California—Berkeley	66	2	4	2	15	12	8	10	7	6
Rice University	44	1	7	0	39	9	8	10	4	14
University of Virginia—Main Campus	70	4	3	0	22	2	7	12	7	6
Washington University in St. Louis	37	7	0	0	57	0	7	12	7	6
University of Florida	39	4	3	0	50	4	7	12	2	19
Johns Hopkins University	45	3	2	2	46	3	7	12	−1	34
Georgia Institute of Technology—Main Campus	52	4	3	0	39	2	7	12	−13	49
Colorado State University	61	0	5	1	28	4	6	17	4	14
University of California—Davis	43	3	3	0	44	7	6	17	1	24
University of North Carolina at Chapel Hill	72	2	4	0	18	4	6	17	0	29
Massachusetts Institute of Technology	5%	3	2	0	35	8	5	20	5	11
University of Washington—Seattle Campus	62	1	4	0	24	9	5	20	5	11
California Institute of Technology	66	2	3	0	14	15	5	20	4	14
Pennsylvania State University—Main Campus	68	3	2	0	22	5	5	20	4	14
Ohio State University—Main Campus	44	1	3	1	49	2	5	20	3	18
Duke University	45	3	1	1	1	49	5	20	0	29
Cornell University	55	0	4	0	36	5	4	26	2	19
Emory University	30	2	2	0	62	4	4	26	0	29
University of Michigan—Ann Arbor	64	3	1	0	26	6	4	26	−3	42
Virginia Polytechnic Institute and State University	44	1	2	0	47	6	3	29	5	11
University of Arizona	49	0	3	0	45	3	3	29	2	19
University of Colorado at Boulder	85	0	3	0	8	3	3	29	0	29
Indiana University—Bloomington	59	3	0	0	34	3	3	29	−1	34
University of Utah	60	0	3	0	31	6	3	29	−2	38
Northwestern University	55	2	1	0	37	5	3	29	−3	42
Michigan State University	35	0	1	1	62	1	2	35	0	29
Princeton University	42	1	1	0	52	4	2	35	1	24
Stanford University	46	0	2	0	44	8	2	35	1	24
Yale University	57	0	2	0	37	4	2	35	1	24
The University of Texas at Austin	56	1	1	0	38	4	2	35	−3	42
University of Maryland—College Park	46	0	2	0	46	6	2	35	−12	48

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Table 8. continued

	2005−2009								1995−2009	
Institution[a]	White, %	African-American, %	Hispanic, %	Native American, %	Nonresident, %	Asian, %	URM, %	Rank for URM	Growth URM, %	Rank for Growth URM
Iowa State University	40	0	1	0	56	3	1	41	2	19
University of Pittsburgh—Pittsburgh Campus	42	1	0	0	53	4	1	41	1	24
University of Minnesota—Twin Cities	65	1	0	0	32	3	1	41	−1	34
University of Chicago	42	0	1	0	51	6	1	41	−2	38
University of Pennsylvania	44	1	0	0	50	5	1	41	−3	42
University of Southern California	18	0	0	0	73	9	0	46	−1	34
Columbia University in the City of New York	42	0	0	0	49	8	0	46	−2	38
University of Illinois at Urbana—Champaign	68	0	0	0	23	9	0	46	−2	38
University of Wisconsin—Madison	71	0	0	0	25	3	0	46	−3	42

[a]University of California—San Francisco is omitted from this table because of gaps in the IPEDS data.

Percent Minority Faculty was correlated with higher minority student representation. However, neither *Percent Minority Faculty* nor *Total Degrees* were significantly related to the growth of the Hispanic population or any other specific group represented in chemistry programs.

The population of international students grew the most of any group, with 11% growth over the 14 years covered in the data. Again, total degrees granted did not significantly predict nonresident representation, and neither total degrees nor percent of minority faculty were significantly related to growth in degrees awarded to nonresident students.

The trends in individual departments are shown in Table 8, ordered by total %URM.

Table 9 summarizes stand-out departments on both the high and low end for representation and growth in degrees to URM students. The top- and bottom-ranked schools for both representation and growth are included in the table. Departments with both high representation and high growth include Louisiana State University, Purdue University, Florida State University, Harvard University, and three University of California campuses. Departments with low or no URM students and concurrently low growth included the University of Pennsylvania and University of Wisconsin—Madison. Texas A & M University showed high representation with low growth. Due to the overall low percentages of minorities, institutions that showed high growth also tended to rank well in URM representation.

DISCUSSION

The analysis provides an overview of growth in the number of chemistry Ph.D.s and of representation of women and minority students among those earning Ph.D.s, as summarized in Table 10. This period saw the greatest gains in representation and growth for women. From single-digit representation in the 1960s, now 36% of all Ph.D.s are granted to women. Larger departments tend to graduate slightly fewer women, but larger departments also have seen more growth over time in women's representation. Interestingly, departments with higher percentage of women faculty also tend to have fewer women Ph.D.-earners, even when department size is held constant.

Underrepresented minority students have both low representation and low growth in Ph.D.s earned from chemistry departments. While the total number of white students earning Ph.D.s has decreased substantially since 1995, most of the relative decrease is because of the influx of nonresident students earning degrees. Both Hispanic and white representation are higher in larger departments.

In the next sections, we discuss possible explanations for these quantitative trends. We first examine relationships based on the quantitative data, then consider programmatic and environmental factors from our interview data and from the literature that contribute to high diversity in STEM departments.

Recruitment and Retention of Women

The data suggest that targeting women may be one strategy for growth or sustainability of a program. However, they do not indicate whether small departments are more successful in recruiting women to their Ph.D. program, or in retaining them to graduation (or both). In a competitive environment, there may be more pressure on smaller departments to recruit aggressively and creatively to maintain class size. Small departments may pay more (real or perceived) attention to

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Table 9. Departments Distinctive in Representation and Growth for Ph.D.s Awarded to URM Students

	High Growth (Ranked in Top 10)	Low Growth (Ranked in Bottom 10)
High representation (ranked in top 10)	University of California—Los Angeles Florida State University University of California—Irvine University of California—San Diego Louisiana State University Purdue University Harvard University	Texas A & M University
Low representation (ranked in bottom 10)	—	University of Pennsylvania University of Wisconsin—Madison

individual applicants and that may be appealing to women applicants. Indeed, prior work in mathematics has shown that women students concentrate in less prestigious types of institutions.[45]

We find no significant statistical relationship between the percentage of Ph.D.s awarded to women and the percentage of women faculty. This is somewhat counterintuitive given studies that have detected positive associations between undergraduate degrees in STEM awarded to women and the proportion of women faculty in their department, and that suggest the importance of women faculty as role models and/or as signals to women that they may join an occupation.[45,46] Other studies too suggest associations between women students' success and the representation of women on the faculty.[24] In this study, it may be the case that the percentages of women faculty are too low overall to detect differences: nearly all departments were below the level of what is generally considered a "critical mass."[47,48]

Recruitment and Retention of Minority Students

It is notable that no department achieved high minority representation without also seeing high minority growth. That is, departments had actively worked to increase their minority representation; it was not automatic. In interviews with department heads, issues with geographic location were sometimes suggested to be barriers to recruiting racially diverse students. However, the presence of Midwestern universities among both positive and negative outliers suggest that the racial and ethnic diversity of the university's home region is not a determining factor; most U.S. universities recruit Ph.D. students nation-wide. One exception to this general statement may be Louisiana State University, which has specifically targeted students from minority-serving institutions in its region.

Given the very low racial and ethnic diversity among chemistry Ph.D. graduates overall, and the lack of clear explanatory factors in the quantitative data alone, it is worth looking more closely at publicly available information from two departments with very high success. The Web site for Purdue's chemistry department (see Box 1) features an explicit statement about the value and meaning of diversity that references faculty, students, and staff and provides a link to the department's diversity plan. That plan names specific strategies for recruitment, retention, climate, mentoring, monitoring, and assessment and, importantly, identifies who is responsible for carrying them out. Explicit use of data is made to identify the problem, monitor progress, and celebrate accomplishments, and there are signs of support and alignment with diversity goals set at the college and university level. Purdue has built recruitment pipelines to specific minority-serving institutions and developed peer mentoring programs for graduate students.

Box 1: Strategies To Increase Diversity in Ph.D. Programs

The Woodrow Wilson Foundation reviewed mechanisms for recruiting and retaining minority Ph.D. students:[57]

- Diversity and the Ph.D., Woodrow Wilson Foundation, 2005

These institutional resources offer good examples of approaches taken by specific departments and graduate schools:[58−60]

- Statement on Diversity and Plan for Broadening Participation, Department of Chemistry, Purdue University
- Recruiting and Outreach, Rackham Graduate School, University of Michigan. See especially "Recruiting for Diversity, Ph.D."
- Recruiting and Retaining Minority Students, The Graduate School, University of Washington

Institutions supported by the National Science Foundation's ADVANCE program to address gender equity on the faculty have produced materials on unconscious bias for evaluating faculty that are also useful in considering graduate admissions:[61,62]

- Raising Awareness of Unconscious Assumptions and Their Influence on Evaluation of Candidates, Office of the Provost, Boston University
- Reviewing Applicants: Research on Bias and Assumptions, Women in Science and Engineering Leadership Institute (WISELI), University of Wisconsin−Madison

The Royal Society of Chemistry (U.K.) studied "good practice" in the recruitment, retention, and career progression of academic chemists and found that good practice benefits students and faculty, men and women, alike. The reports feature a departmental checklist and many examples of how departments made progress:[63,64]

- Good Practice in University Chemistry Departments, 2004
- Planning for Success—Good Practice in University Science Departments, 2008

Louisiana State's Web site also has an explicit statement about diversity and examples of specific initiatives and their leaders. The department's five-year strategic plan includes diversity goals that are tailored to the department's context and opportunities. LSU's story emphasizes the deliberate building of relationships with Historically Black Colleges and Universities, by charismatic leaders who took initiative coupled with engagement of the whole faculty in recruitment and retention.[49,50] The contrast is striking between the explicit attention to diversity on these departmental Web sites versus other sites we reviewed where

Table 10. Summary of Results for All Models[a]

Group	Percentage for Group (Top 50 Sample, 2005–2009)	Growth during Study Period for Group (22 Years or 14 Years), %	t-Values for HLM Models: Year	Total Degrees Predicts Percentage of Women	Total Degrees Predicts Growth	Female Faculty Predicts Percentage of Women	Female Faculty Predicts Growth	Minority Faculty Predicts Percentage of Women	Minority Faculty Predicts Growth
Women	36	14	12.1**	−2.1**	2.0*	−1.7*	−2.1*	NA	NA
White	51	−11	−5.6**	2.7**	—	NA	NA	—	—
URM	5	1.6	2.4**	—	—	NA	NA	−1.9*	—
Hispanic	3	1.4	3.0**	2.8**	—	NA	NA	—	—
International	37	11	5.0**	—	—	NA	NA	—	—

[a]*Denotes significance at $a < 0.05$ level. **Denotes significance at $a <0\ 0.01$.

the word "diversity" is not used at all. This undoubtedly sends signals—intended or not—to prospective students.

Strengths and Limitations of the Study

A strength of the study is its reliance on publicly available, disaggregated data that are gathered annually in a standardized fashion and that count all degrees awarded. However, the study findings are limited by the relatively short time span in which data are disaggregated, especially for race/ethnicity where small and noisy numbers currently limit what can be discerned about time-based trends. Moreover, as an assessment of strategies to diversify a department, graduation data are inherently time-delayed from the onset of changes in recruitment and retention that a department might pursue. Future work probing trends on a longer time scale will also need to resolve the changes to demographic categories made by IPEDS in the data set over time. At present, data on graduate admissions and persistence are neither widely available nor standardized in form, thus limiting the potential to build a more complete quantitative model that might distinguish program-level success in admissions from success in retention.

Implications for Practice

In this study, by focusing on individual departments that may have quite different local environments, we can identify some with particular success in recruiting and educating a diverse group of doctoral chemists. But quantitative data alone do not explain the reasons for the observed trends; in this case, they do not even offer strong hypotheses for further exploration. Instead, we gain some insight by consulting a separate analysis of interviews with department chairs and graduate program directors[12] where we found that diversity was an issue of varying salience in departments. Some interviewees described active and intentional efforts to increase diversity in their departments, while others did not see this issue as high on their priority list.

These interviews revealed that many departments perceived themselves as average in their representation of women, when in fact the quantitative data made clear that some of these very departments were not keeping pace with national trends. In contrast, interviewees from departments with strong records of women's or minority representation were more likely to be able to cite specific departmental data and specific actions taken to monitor it. This observation suggests that awareness of the data may be an important first step to progress.

Departments that had been most successful in increasing diversity tended to couple stepped-up recruitment efforts with specific plans to support and retain students after they arrived on campus. They described targeted scholarships, strengthened mentoring, support of graduate student groups for peer mentoring, and earlier and more frequent benchmarking of student progress toward the degree. When such ventures were successful in increasing diversity, departments observed a "snowball" effect: by building a critical mass of under-represented students, recruitment and retention of future students began to "take care of themselves". Moreover, these departments found that some practices that were helpful to underrepresented students were helpful to all, such as improvements to graduate student handbooks and periodic, formal reviews of progress toward the degree, thus ensuring students received individual advice and did not fall through the cracks. Such "rising tide" approaches may be particularly helpful in today's policy climate as affirmative action strategies for recruitment are being challenged in the courts. The approaches reported by our sample are consistent with those documented by other successful programs.[51,52]

In addition to these efforts targeted to the graduate student experience, broader efforts to improve departmental climate had also had a positive impact. Generational differences in expectations of work, particularly regarding work/life balance, had heightened departments' awareness of departmental climate and culture as factors that influenced both faculty and graduate student diversity. One department reported positive spin-offs from institutional efforts to improve climate through an ADVANCE project on their campus.[53,54] Another department leader observed that his program's deliberate efforts to increase the interdisciplinary flavor of their research had also proven particularly attractive to women graduate students.

The literature increasingly points to the importance of the department as the unit of change. Sonnert, Fox, and Adkins establish that growth in STEM degrees to undergraduate women is associated with departmental, not institutional characteristics.[46] And in their study of the effectiveness of programs for undergraduate women in science and engineering (WISE), Fox, Sonnert, and Nikiforova contrast individual and structural approaches to improving women's representation.[55] Individual approaches focus on women themselves: the attitudes, behaviors, aptitudes, skills, and experiences that may affect their participation and performance in science, such as confidence or motivation. Structural approaches focus on features of the setting in which women work or pursue education, such as patterns of inclusion or exclusion in research groups, selective access to human and material resources, and different practices and standards of evaluation that may operate for women compared to men. These researchers found that WISE programs were most successful in increasing the proportion of women graduates when they took an institutional or structural perspective on the issues, problems, and solutions of women in science and engineering, as opposed to an individual or student-centered perspective.

Malcom and Malcom-Piqueux describe low diversity in the STEM fields, and the slow rate of improvement, as the "worst case" (ref 56, p 176) in higher education. Yet they point out, research demonstrates that diversity becomes self-sustaining when a critical mass is reached (ref 56, p 176):

> *Sustainable diversity results from environmental changes—that is, changes in culture, curricula, and instruction; quality and quantity of supportive practices; and faculty behaviors, attitudes, and expectations—that support the success of all students.*

Our data likewise suggest that diversity is not automatic, but it can be improved, department by department, through active effort to monitor and improve the representation of women and minorities succeeding and earning degrees. Box 1 suggests some resources for faculty who wish to begin that work in their own department.

AUTHOR INFORMATION

Corresponding Author

*E-mail: Sandra.Laursen@colorado.edu.

Notes

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