TPI Technology Policy International, LLC

EVOLVED PRACTICES OF U.S. GRADUATE EDUCATION

A Report to JST

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December 2023

Technology Policy International, LLC

www.technopoli.net

PREFACE

The study underlying this report was commissioned by the Washington, D.C., office of the Japan Science and Technology Agency (JST) and was conducted by Technology Policy International, LLC.

The opinions expressed in this report do not necessarily reflect the views of JST or of other institutions with which the TPI partners are affiliated.

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INTRODUCTION

This report addresses the features of the U.S. graduate education system that encourage or discourage:

- Interdisciplinary education[1]
- Work focused on societal issues
- Diversity of students

The report also provides examples of these features in leading U.S. universities.

The report is based on an examination of several case universities as well as the authors' experiences as administrators, faculty, and students at multiple universities, including the case universities.

There are differences among U.S. universities as well as substantial differences among schools and departments within universities. In some regards, the differences among different departments and programs within a university are more pronounced than the differences among similar departments and programs in different universities. Because of these differences, we have narrowed the scope of the report to focus primarily on PhD programs in science and engineering. We note some of the differences with master's and professional programs, as well as programs in the arts and humanities, which all differ from PhD science and engineering programs.

This report is a companion to an earlier report that focused on interdisciplinarity in undergraduate education.[2]

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[1] This report uses "interdisciplinary" to include "multidisciplinary" and "transdisciplinary." While some authors make careful distinctions between these terms, denoting different levels of integration of the separate disciplines, the distinction are not important for this report.

[2] David W. Cheney, Christopher T. Hill, and Patrick H. Windham. Cross-Disciplinary Education in U.S. Colleges and Universities, Part I: Undergraduate Students. A Report to JST. Technology Policy International. March 2023.

The report begins with a comparison of graduate programs with undergraduate programs and activities with respect to:

- Recruitment & admissions
- Financial aid & external funding
- Curriculum
- Roles of research and course work
- Faculty and staff advising/mentoring/personal engagement

We then discuss and draw examples from six case study institutions, highlighting some programs within each institution.

This is followed by a discussion of the main study topics, using examples from the case institutions. These study topics include:

- What are the incentive structures and external conditions that most significantly encourage and/or discourage diversity and boundary-crossing in graduate education?
- How do graduate school programs and opportunities affect the offering of opportunities for graduate students to learn how to apply trans-disciplinary skills to addressing complex social problems?

The report concludes with some general observations and conclusions.

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COMPARISON OF GRADUATE AND UNDERGRADUATE PROGRAMS

Graduate and undergraduate programs differ substantially with respect to:

- Recruitment and Admissions
- Tuition, financial aid, and external funding
- Curriculum and the roles of disciplines; accreditation; the roles of research and course work
- Faculty and staff advising, mentoring, and personal engagement

In addition, masters and professional degree programs differ substantially from academic PhD programs with regard to many of these characteristics. The following sections and tables describe the typical patterns of these programs at U.S. universities. These insights are based primarily on the authors' broad experiences with many U.S. universities.[3] Many of these

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[3] These include not only the authors' experiences at the institutions described in this report, but also familiarity with many other institutions through their professional careers.

patterns are also covered in books and studies on the U.S. university system.[4] While these are the general patterns, one can find exceptions to many of them in the great diversity of the American university system.

RECRUITMENT AND ADMISSIONS

Table 1 Compares undergraduate and graduate education with respect to recruitment and admissions. A key point is that undergraduates generally are admitted to a university and can choose or change their major after they are admitted. Graduate students, on the other hand, are generally admitted to a specific graduate program or department.

Table 1. Recruitment and Admissions

Undergraduate	Masters/Professional	PhD Programs
Students are admitted to the university/college	Students are admitted to the graduate school and a specific graduate program	Students are admitted to graduate school and a specific program, in consultation with departments and individual faculty members
Students are recruited through high school visits, college guides and rankings, and advertising	Students are recruited through grad school guides, rankings, and advertising	Students are recruited through the reputation of departments and individual faculty members; as well faculty connections and recommendations
Students select universities based on rankings & guides, and advice from counselors/ family	Students select programs based on reputation and program characteristics	Students select programs based on reputation, specific research strengths, and individual faculty

[4] These include: Geiger, Roger L. Research and Relevant Knowledge: American Research Universities Since World War II. New York: Oxford University Press. 1993. Crow, Michael M. Designing the New American University. Baltimore: Johns Hopkins Press. 2015. John V. Lombardi, How Universities Work. Baltimore: Johns Hopkins Press 2013

Admissions are based on grades, test scores, essays, recommendations	Admissions are based on grades, test scores, essays, recommendations, and work history	Admissions based on grades, test scores (sometimes), essays, recommendations, research experience and interests, and fit with faculty research interests

TUITION, FINANCIAL AID, AND EXTERNAL FUNDING

Table 2 compares undergraduate and graduate education with respect to how the education is paid for. Undergraduate, as well as professional and masters' programs are usually paid for by the student (or their family), often with some financial assistance from loans, fellowships, campus jobs, or other forms of assistance. PhD programs, especially in science and engineering, are often funded by the university through teaching assistantships or research assistantships (usually funded by research grants) that cover tuition and pay a stipend to cover basic living expenses.

Table 2. Tuition, Financial Aid, and External Funding

Undergraduate	Professional/Masters	Research/PhD
Paid by the student/family with some financial aid and student loans.	Paid primarily by the student or their family. Some limited research/teaching assistantships may be available.	Typically funded by research assistantships, teaching assistantships, and fellowships.
Financial aid comes from university funds, government loans and fellowships, and foundations. Students may also work at campus jobs.	Financial aid from government loans, some fellowships. Some students get assistance from employers.	Teaching assistantships are usually from university funds. Research assistantships are typically funded by Federal or other grants. There are some NSF and other fellowships.

CURRICULUM - ROLES OF DISCIPLINES; ACCREDITATION; ROLES OF RESEARCH AND COURSE WORK

Table 3 compares undergraduate and graduate education with respect to their disciplinary focus, the accreditation of programs, and the extent to which degrees are based on coursework versus research. Undergraduate and master's degrees are based more on coursework whereas PhD degrees are research based and highly customized.

Table 3. Disciplinarity, Accreditation, and Coursework

Undergraduate	Professional/Masters	Research/PhD
Undergraduate degrees generally require taking courses in multiple disciplines. 30-80% of courses are outside of the major discipline	Some masters courses are all in one discipline. But many professional/masters programs are problem/need driven and are interdisciplinary	Students take the courses needed for their research, which may be in one or several disciplines.
Regional accreditation organizations accredit the whole institution. Some specific programs may also be accredited (e.g. engineering programs are accredited by ABET)	Some professional programs (e.g., law, medicine, pharmacy, business) are accredited by the relevant professional society. Most other master's program are not specifically accredited, but rely on whole institution's accreditation.	PhD programs are mostly not specifically accredited, but are within accredited universities.
Degrees are based 90 to 100% on course work. There may be some limited undergraduate research (<10%)	Degrees are mostly (70-100%) coursework; some limited (usually <30%) research. Many masters degrees require a thesis or major project.	There is some coursework (20-60% of effort); usually more than half of effort is research (40 to 80%).

FACULTY AND STAFF ADVISING, MENTORING, AND PERSONAL ENGAGEMENT

Table 4 compares the interaction of students with advisors and faculty between undergraduate and graduate education. PhD programs are characterized by much deeper interactions between students and their faculty advisors than undergraduate or professional/masters programs.

Table 4. Faculty and Staff Advising, Networking, and Personal Engagement

Undergraduate	Professional/Masters	Research/PhD
Advisors are assigned to help select courses and aid progress toward degree. Universities increasingly use professional advisors (rather than faculty members).	An advisor is assigned to help select coursework and ensure progress toward degree.	An advisor assigned for early course work. The student research/dissertation advisor plays key role in guiding student's course work and defining dissertation topic.
The degree of faculty involvement with students varies – there is more in small colleges/universities and less in large universities.	Degree of faculty involvement with students varies, but is often greater than for undergraduates and less than for PhD students.	There are typically close interactions between PhD students and faculty in same research group.
Students may have an honors thesis/capstone advisor in their senior year.	May have thesis advisor in second year.	Dissertation advisor/chair of dissertation committee plays a major role in guiding PhD work.

HOW DIFFERENCES BETWEEN GRADUATE AND UNDERGRADUATE PROGRAMS AFFECT INTERDISCIPLINARITY AND SOCIETAL RELEVANCE

Undergraduate and graduate programs differ significantly with respect to what drives interdisciplinary education and education focused on societal needs.

At the undergraduate level, universities are motivated to attract students – tuition is a main source of funding. Some students are seeking specific skills needed for identified careers, but others are seeking broader educations that may position them for graduate studies or a variety of careers. Universities seek to keep their program offerings up to date – aligned with evolving fields, employer needs, and student interest in societal problems. Interdisciplinary programs are a way to attract and engage students, and let faculty engage in interesting and socially relevant topics.

At the Masters and Professional level, universities are also motivated to attract tuition-paying students, and students are generally focused on the skills they need for the careers they have chosen. Many interdisciplinary masters and professional programs train students for emerging interdisciplinary occupations.

For academic PhD programs, interdisciplinarity and social relevance are primarily driven by directions in research funding. Research priorities are in turn driven by the research community and external stakeholders (government, foundations). This is discussed later in this report.

SIX INSTITUTIONS/PROGRAMS FOR STUDY

To analyze and provide illustrations of interdisciplinarity and societal relevance in U.S. graduate education, we looked in more detail at six U.S. institutions. These are:

- Stanford University
- Massachusetts Institute of Technology (MIT)
- Brown University
- George Mason University
- University of California, Berkeley
- Arizona State University

These include a mix of elite private universities (Stanford, MIT, and Brown) and well-regarded public universities (UC Berkeley, George Mason University, and Arizona State Universities). All are strong in science and technology; most are regarded as innovative in curriculum and are known for their interdisciplinary work.

Four of these (Stanford, MIT, Brown, and George Mason) were the same institutions we analyzed as part of our previous study of undergraduate education. The report authors have direct experience with five of these (Stanford, MIT, Brown, George Mason, and Berkeley) as students, faculty members, or as an administrator.[5]

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[5] Windham was a student and is a lecturer at Stanford. Hill was a research professor and Cheney was a graduate student and research associate at MIT. Cheney was a student at Brown University. Hill was a professor and Vice Provost for Research, and Cheney was a PhD student and adjunct faculty at George Mason University. Windham was a graduate student at Berkeley.

While the six institutions are not a random selection of universities nor are not perfectly representative of all U.S. research universities, they illustrate the forces at play in the U.S. system and the types of graduate programs that are found across many U.S. universities.

STANFORD UNIVERSITY

BACKGROUND

Leland Stanford Junior University – named for Leland Stanford, Junior, the son of university founders Leland and Jane Stanford – is one of the top research universities in the United States. It is a private school that was founded in 1885 and officially opened on October 1, 1891.[6]

Located in California's Silicon Valley, it is known for both research excellence and the role its faculty, students, and alumni have played in high-technology entrepreneurship. The university has often created trans-disciplinary research programs and trans-disciplinary graduate degrees.

In the Autumn of 2022, 7,761 undergraduate students and 9,565 graduate students (including professional students in medicine, law, and business) were enrolled at Stanford. Stanford currently has 2,304 faculty members. It is a wealthy university: its "endowment" (the money it owns) is $36.3 billion.[7] It also owns a large amount of land, and it earns additional money by leasing some of that land to companies.

Stanford is very strong in several STEM fields, particularly electrical engineering, computer science, and biomedicine. It has several Nobel Prize winners. It also manages a major Department of Energy facility: SLAC National Laboratory. (SLAC's original name was the Stanford Linear Accelerator Center.)

During Federal Fiscal Year 2022 (October 1, 2021, to September 30, 2022), Stanford's total research and development (R&D) expenditures were $1,384,555,000. That year, among all U.S. universities, it ranked 10th in total research spending. Of that total, $860,125,000 came from the federal government; Stanford ranked 9th in federal R&D funds.[8]

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[6] "Stanford University," *Wikipedia*, https://en.wikipedia.org/wiki/Stanford_University. For additional information on Stanford's history, see: Stanford University, "A History of Stanford," https://www.stanford.edu/about/history/.
[7] Stanford University, "Stanford Facts," https://facts.stanford.edu/.
[8] National Science Foundation, "Table 21: Higher education R&D expenditures, ranked by FY 2022 R&D expenditures: FYs 2010-22" and "Table 24: Federally financed higher education R&D expenditures, ranked by 2022

HISTORY AND CULTURE

MAJOR EVENTS IN STANFORD'S HISTORY

Several related factors have greatly influenced Stanford's history: (1) its role as a major California institution of higher education; (2) its long connection to the California economy, especially the electronics industry; and (3) beginning in the 1960s, the strong desire of Stanford leaders to change it from being a regional university to a world leader in research and education.

California became a U.S. state in 1850, and for many years it had few institutions of higher education. The Catholic Church created some colleges during the Spanish and Mexican eras, and then in 1868 the California government created the University of California's first campus, at Berkeley. (A later section of this report discusses UC Berkeley and its trans-disciplinary programs.) But the growing state still had relatively few universities.

When Leland and Jane Stanford wanted to create a memorial to their son, they saw an opportunity to create a new private university, based on the famous universities in the eastern United States. (The Stanfords particularly liked Cornell University, in New York State, as a model.) When Stanford began operating in 1891, it became the second major university in Northern California – after Berkeley – and particularly attracted affluent young men and women from San Francisco and other parts of California.[9]

From its earliest days, Stanford had a strong engineering school. And in the early 20th century, Stanford graduates began to contribute to California's new electronics industry. In 1909 Stanford graduate Cyril Frank Elwell founded what became Federal Telegraph Company, located in Palo Alto, next to the Stanford campus. The company worked on early radio technologies. The U.S. Navy had a strong interest in radio technology, and during World War I the Navy bought Federal Telegraph, selling it again after the war ended. In the years that followed, Northern California became a center for entrepreneurial companies in early radio and television.

Before and after World War II, Fred Terman, a Stanford engineering professor (and later Stanford's provost, the university's number two official) saw an opportunity to build a local San Francisco Bay Area electronics industry. Earlier, California had trouble establishing successful

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R&D expenditures: FYs 2010-22," both tables available at: https://ncses.nsf.gov/surveys/higher-education-research-development/2022#data.

[9] Stanford University," *Wikipedia.* This paragraph and the following paragraphs draw heavily on the Wikipedia article and the Stanford history cited earlier.

manufacturing companies, because the state had high labor costs. But the new electronics industries offered an opportunity for California. In the late 1930s, Terman and other Stanford professors helped young Stanford graduates establish companies such as Varian and Hewlett-Packard. Then after World War II, the U.S. Government – particularly the Defense Department – began to invest large amounts of money in electronics and aerospace. Stanford's strong departments in electrical engineering and physics received substantial research funding; its affiliated Stanford Research Institute (now SRI International) became a major center for federally-funded computer research; and both large companies such as Lockheed and new entrepreneurial companies built factories in the region.

Three other developments in the 1950s also played major roles in the growth of both Stanford and Silicon Valley. First, Fred Terman established the Stanford Industrial Park, a place on Stanford land where entrepreneurial companies such as Hewlett-Packard could build facilities. Related, engineers in these local companies could take continuing education courses at Stanford. The university and companies developed close ties, and Stanford professors themselves sometimes became entrepreneurs. Second, the physicist William Shockley – a Nobel Prize winner for his role in creating the transistor – established a company in the region. (His mother lived in Palo Alto.) Shockley became a Stanford professor and created the region's pioneering semiconductor company – starting one of Silicon Valley's most famous industries. Third, in the late 1950s Stanford decided to move its medical school from San Francisco to the main campus in Palo Alto. As a later section of this report will discuss, this development later facilitated valuable trans-disciplinary research and cooperation between the Stanford Medical School and the Stanford School of Engineering.

In addition, beginning in the 1960s Stanford made the transition from a regional university for affluent California students to a more national and higher-prestige institution. Federal research grants, its own land and real estate operations, and donations from wealthy alumni helped it become a world-class university.

Since the 1960s, Stanford has continued to have close ties with what is now called Silicon Valley. The university has a very pro-entrepreneur culture, and in fact many professors and many students – undergraduates as well as graduate students – aspire to start companies. Because Stanford has world-class students, professors, and research, its people are well placed to start companies in new emerging areas of science and technology. Stanford professors, students, and alumni have played important roles in the creation of several industries, including computing, the Internet, biotechnology, and now artificial intelligence.

One should not exaggerate Stanford's role in the creation of Silicon Valley. Berkeley has also been an important source of skilled engineers. And large companies such as Lockheed, huge Defense Department investments, and entrepreneurs from many places all contributed to

Silicon Valley's growth. Still, Stanford has been one important factor in Silicon Valley's history. Its professors, students, and alumni have invented new technologies and have helped to create important companies from Hewlett-Packard to semiconductor firms to Genentech and other biotechnology firms to Internet firms such as Cisco and Google.

TRANS-DISCIPLINARY RESEARCH AND GRADUATE EDUCATION

Given its culture and history, today Stanford has strong incentives to create trans-disciplinary research and education programs and the wealth and resources that allow it to fund those programs.

Because Stanford's culture emphasizes research excellence and entrepreneurship, there are three reasons why it may want to create trans-disciplinary research and education programs. First, it wants to attract outstanding professors and students, and many of whom want to work on exciting new interdisciplinary research questions. For example, bioengineering and now artificial intelligence are fields that attract faculty and students. Second, some Stanford professors and students may also want to conduct "cutting-edge" research in fields such as artificial intelligence because that research can help them start new companies. Third, Stanford wants to compete successfully for new government and private research funds, and some of that funding is in trans-disciplinary fields such as quantum computing or bioengineering.

As a wealthy university, Stanford also has the resources necessary to create new research and education programs.

We should not exaggerate the extent of trans-disciplinary graduate education at Stanford, because most Stanford PhD students continue to receive degrees in established academic departments. However, Stanford does offer graduate students many opportunities for trans-disciplinary research and education. Here are some key points:

- In addition to long-established academic departments, today Stanford also has departments based on new disciplines, e.g., Materials Science and Engineering, Computer Science, and Bioengineering.

- Within some departments, students may study new sub-fields, e.g., computational biology in life sciences departments.

- PhD students may take courses in other departments, and professors from other departments may be on a student's PhD thesis committee.

- Stanford has large interdisciplinary "institutes" and smaller "centers" that allow faculty and students from different departments to work together.

The next section of this report discusses several Stanford trans-disciplinary programs that illustrate these points.

EXAMPLES

BIO-X

Bio-X, created in 1998, is an interdisciplinary research and education program housed in the Clark Center (a building named for James Clark, the entrepreneur and former Stanford professor who donated money for it). The program's website summarizes its history.

> A grassroots movement among Stanford faculty … resulted in a bold enterprise known as Bio-X, created to facilitate interdisciplinary research and teaching in the areas of bioengineering, biomedicine, and bioscience.
>
> In September of 1998, [Stanford leaders] created a Planning Committee consisting of faculty from the schools of Engineering, Medicine, and the Humanities and Sciences. This group developed Stanford Bio-X, and, thanks to a significant lead gift from James H. Clark as well as additional support from Atlantic Philanthropies, the concepts and the construction of a radical new interdisciplinary research building came to life in 2003.
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> Since its establishment in 1998, Bio-X has operated across all seven schools [of the university] and has charted a new approach to life science research by bringing together the combination of experts – medical doctors, scientists, engineers, and others – needed to tackle the complexity of the human body. With its home base in the James H. Clark Center, Bio-X operates both literally and figuratively at the crossroads of medicine, science, and engineering, drawing faculty and students from all seven schools across the university.
>
> The Clark Center, which houses 45 state-of-the-art labs, is specifically designed to encourage purposeful and serendipitous encounters among faculty and graduate students to foster fruitful collaborations. It serves as the physical embodiment of Bio-X and is a magnet engaging over 600 Stanford faculty to study life systems at levels of complexity ranging from the molecular to the behavioral. Bio-X furnishes these collaborators with critical resources – seed grants, graduate fellowships, undergraduate student support, and venture funds – to undertake very early-stage research. Like an

> incubator, Bio-X provides the organizational structure and angel funding to try bold new ideas that are too unproven and interdisciplinary for traditional funding agencies.[10]

Several features of Bio-X are important. First, most graduate students who work in Bio-X laboratories still get their PhD degrees from regular, established academic departments. Second, however, the Clark Center's laboratories allow students and faculty from different departments to work together and do new types of research. In fact, the Clark Center is physically located between the Stanford School of Medicine and the Stanford School of Engineering, making it easy for faculty and students to work together. Third, Stanford's general emphasis on advanced research and entrepreneurship is very prominent at Bio-X, as shown by the program's policy of providing seed money for work on "bold new ideas."

DESIGN SCHOOL

The Hanso Plattner Institute of Design (also called the Design School or "d.school") is a multidisciplinary program that teaches students methods for designing new products and services that meet customer needs. It is located within the Stanford School of Engineering. The d.school offers bachelor's and master's degrees but not its own PhD degrees. However, PhD students in regular academic departments may take courses in the d.school and participate in its research.[11]

The d.school brings together students and faculty to design potential solutions to real-world needs. The program is highly interdisciplinary. Its approach, says one of its webpages, is "radical collaboration:"

> To inspire creative thinking, we bring together students, faculty, and practitioners from all disciplines, perspectives, and backgrounds—when we say radical, we mean it! Different points of view are key in pushing students to advance their own design practice. Our methods become a shared language for groups to navigate the ups and downs of messy challenges.[12]

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[10] "Bio-X History," https://biox.stanford.edu/about/biox-history.

[11] The d.school has two websites: "Hasso Plattner Institute of Design (d.school)," https://engineering.stanford.edu/get-involved/support-engineering/funding-initiatives/hasso-plattner-institute-design-dschool, and "Welcome," https://dschool.stanford.edu/.

[12] "How we do it," https://dschool.stanford.edu/about.

DOERR SCHOOL OF SUSTAINABILITY

The new Doerr School of Sustainability is another example of trans-disciplinary graduate education and research at Stanford. Created in 2022, it is a greatly expanded version of the earlier School of Earth, Energy, and Environmental Sciences ("Stanford Earth").[13] It is also an example of Stanford receiving funds from a very wealthy donor and using those funds to start new programs.

The Doerr School's website emphasizes its interdisciplinary focus:

> In recent years, as Stanford Earth engaged more on exploring land, ocean, water and climate systems, and the environmental changes within them, Stanford became a leader in interdisciplinary education. The school launched the undergraduate Earth Systems Program in 1992 and the graduate Emmett Interdisciplinary Program in Environment and Resources (E-IPER) a decade later. Those interdisciplinary educational programs reflect the need to bring ideas from multiple disciplines to bear on complex problems such as those facing the planet. More recently, the school opened an educational farm and a program dedicated to preparing students to lead sustainability efforts.
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> That same need for interdisciplinary collaboration to generate solutions inspired the creation of Stanford's Woods Institute for the Environment and the Precourt Institute for Energy. Both formed as independent institutes under the Vice Provost and Dean of Research as a way of bridging scholarship on issues that require multiple viewpoints. For more than 15 years, the institutes have fostered research collaborations to protect our natural environment and to generate new solutions that produce sustainable, affordable, and secure energy for all. Those institutes have joined the Doerr School of Sustainability.[14]

The Doerr School has several regular academic departments (which themselves are highly interdisciplinary) and three interdisciplinary programs that offer their own bachelor's, master's, and PhD degrees.

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[13] The Doerr School's website is: "Stanford Doerr School of Sustainability," https://sustainability.stanford.edu/. Information about its departments and interdisciplinary program is available at: "Admissions and education," https://sustainability.stanford.edu/admissions-and-education.

[14] "History," https://sustainability.stanford.edu/history.

- The departments are: Civil and Environmental Engineering; Geophysics; Earth and Planetary Sciences; Earth System Science; Energy Science and Engineering; Oceans; and Environmental Social Sciences.[15]
- The School also has three interdisciplinary programs: the Earth Systems Program; the Emmett Interdisciplinary Program in Environment and Resources; and the Change Leadership for Sustainability Program. These three programs offer degrees for undergraduate, masters, and PhD students.
- The School has several institutes and centers for interdisciplinary research and education. These include the Woods Institute for the Environment; the Precourt Institute for Energy; and the Sustainable Societies Institute.
- The Doerr School also has a Sustainability Accelerator to help the School's entrepreneurs.

MIT

BACKGROUND

MIT (the Massachusetts Institute of Technology) is a large (11,900 students, with 7200 graduate, 4700 undergraduate) private institution located in Cambridge, Massachusetts, just across the Charles River from Boston.

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[15] The Doerr School created the Department of Environmental Social Sciences in December 2023. An article in the Stanford student newspaper provides details about the new department, including these comments from Professor William Barnett, who will chair the department: "Barnett said this change doesn't seek to supplant Doerr's existing interdisciplinary programs. Instead, its goal is to add a level of depth to the social science aspects of the program. 'The interdisciplinary programs are for developing students and scholarship that cuts across science, engineering and social science,' Barnett said. He said the department will improve existing interdisciplinary programs by adding faculty and programs focused entirely on social sciences." Ellen Kim, "'It's our intention to change the world': Doerr announces environmental social sciences department," *The Stanford Daily*, December 8, 2023, https://stanforddaily.com/2023/12/08/its-our-intention-to-change-the-world-doerr-announces-environmental-social-sciences-department/?utm_campaign=digest&utm_medium=email&utm_source=mailchimp&utm_content=Dec-08-2023?utm_campaign=digest&utm_medium=email&utm_source=mailchimp&utm_content=Dec-08-2023.

MIT is one of the top-ranked higher education institutions both in the U.S. and the entire world. Since it was founded, MIT has emphasized engineering and applied sciences. It has also achieved the highest rankings in several basic sciences, the social sciences (especially economics), management, and a wide array of public policy areas such as energy, environment, innovation, transportation, and science, technology, and society.

MIT has made major commitments to interdisciplinary research and education in the applied life sciences, in informatics, and others, and it pioneered in establishing large-scale collaborations between academic researchers and their counterparts in industry and government laboratories.

Notably, MIT does not have a medical school. On the other hand, through its partnership with Harvard in owning and operating the Broad Institute, MIT has become a premier institution in biomedical and related fields of research.[16] The Broad Institute is an illustration of interdisciplinary research at the most advanced levels.

In 2022, MIT was the 30th-ranked performer of separately funded research, spending some $989 million that year.[17] It also ranked 30th in federally funded research expenditures, which totaled some $531 million.[18] These relatively low rankings for an institution of such importance reflect in substantial measure MIT's choice not to host a medical school. (In the United States the top ranked performers of academic R&D nearly all depend on well-funded, research-intensive medical schools for their high rankings.) The low rankings also reflect the fact that quite a few of the highly ranked institutions in terms of R&D expenditures are considerably larger than MIT as measured by numbers of graduate students and research faculty members.

HISTORY AND CULTURE

MIT was founded in 1861, in part, in reaction to the heavily academic focus of the leading American colleges of the time such as Harvard, Princeton, and Yale.[19] Its founder, William Barton Rogers, saw a need for advanced education on topics of practical interest that combined both "Head and Hand."

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[16] https://en.wikipedia.org/wiki/Broad_Institute

[17] https://ncses.nsf.gov/surveys/higher-education-research-development/2022#data, table 21

[18] Ibid, table 24

[19] https://en.wikipedia.org/wiki/Massachusetts_Institute_of_Technology

MIT's practical focus was reinforced by its designation as the Federal "Land Grant" institution of the Commonwealth of Massachusetts under the Morrill Act of 1862, even though it is a private institution. The Land Grant institutions were established to emphasize education in agriculture and the mechanical arts to support the rapidly growing agricultural and manufacturing economy of the U.S. in the mid-nineteenth century. [20] Nearly all of them are state-supported, public institutions.

MIT has been associated closely with the needs of industry and, increasingly, of government agencies, and has emphasized the applications of scientific and technical knowledge to solve problems of society, ranging from improving health to fighting wars. MIT pioneered large-scale research partnerships with industrial companies and consortia and has hosted many major government-supported research programs, centers and institutes focused on national needs.

MIT was one of the first U.S. academic institutions to embrace and support entrepreneurism by its faculty, students, and graduates. People associated with MIT have played leading roles in building modern American technology-based industry and in inventing and promoting technologies for national defense and for governance in general. MIT was also an early exponent of the need to understand and to educate its students about how technology influences and is influenced by society.

Traditional academic departments based on core disciplines are very powerful within MIT, controlling faculty hiring and promotion, determining core curricula, and influencing budgets. At the same time, MIT has been able to set up a host of interdisciplinary and cross-disciplinary research and education programs at both undergraduate and graduate levels. It also welcomes individual graduate students and faculty members who wish to collaborate in research and education with colleagues in other disciplines and departments.

MIT is unusually flexible in supporting faculty and students to work across boundaries, with the only consistent expectation being that whatever they choose to do, they should strive for and achieve excellence and leadership in the world-wide academic community. MIT today offers nearly 50 interdisciplinary graduate degrees, mostly at the doctoral level.[21]

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[20] https://en.wikipedia.org/wiki/Morrill_Land-Grant_Acts

[21] https://catalog.mit.edu/interdisciplinary/graduate-programs/#degreesofferedtext

EXAMPLES

DOCTORAL PROGRAM IN SOCIAL AND ENGINEERING SYSTEMS (SES).[22]

SES is focused on addressing concrete and societally significant problems by combining the analytical tools and methods of statistics and information sciences with engineering and the social sciences. SES students study problems that correspond to significant societal challenges. This includes analytical research that can be used to inform policy making. Examples include work on combatting systemic racism, climate change, and misinformation in social media.

ESTABLISHED INTERDISCIPLINARY DEGREE PROGRAMS[23]

At MIT a graduate student may apply to enter one of the following established interdisciplinary doctoral degree programs, supervised by a special standing committee of the faculty:

- Computational and Systems Biology (CSB)
- Computational Science and Engineering
- Health Sciences and Technology (HST)
- Oceanography and Applied Ocean Science and Engineering
- Microbiology
- Operations Research
- Polymers and Soft Matter
- Transportation

A somewhat longer list of established interdisciplinary graduate degree programs appears elsewhere on the MIT web site.[24]

INDIVIDUALLY TAILORED DOCTORAL PROGRAMS[25]

At MIT, a student may design an individually tailored doctoral program whose boundaries overlap two or more departments. The initiative for arranging such an interdisciplinary program lies with the student. If the interdisciplinary degree proposal is adequate in scope and depth to meet degree standards, the Office of Graduate Education appoints an ad hoc interdisciplinary

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[22] https://idss.mit.edu/academics/ses_doc/

[23] https://oge.mit.edu/gpp/advanced-degrees/interdisciplinary-degree-paths/interdisciplinary-doctoral-degree/
This description is copied essentially verbatim from the MIT web site.

[24] https://catalog.mit.edu/interdisciplinary/graduate-programs/#degreesofferedtext

[25] https://oge.mit.edu/gpp/advanced-degrees/interdisciplinary-degree-paths/interdisciplinary-doctoral-degree/

committee which is responsible for supervising the entire degree program. The student remains a full member of the department of registration, which monitors academic performance and provides administrative support. A single degree will be conferred by the student's department of registration, with a degree field specific to the approved program.

BROWN UNIVERSITY

BACKGROUND

Brown University is a private research university in Providence, Rhode Island. It is one of the 8 "Ivy League" universities and is the seventh oldest U.S. university, founded in 1764.[26] It is the smallest of the institutions studied in this report. Although it has long had a graduate school, the graduate school has been small compared to the undergraduate programs (although graduate programs have grown recently). In the fall of 2022, there were:[27]

- 7222 undergraduate students
- 2920 graduate students
- 595 Medical students
- 1475 faculty

Brown's Graduate Programs included 50 doctoral programs and 30 master's degree programs. In 2022, Brown awarded 1677 Baccalaureate degrees, 875 Master's, 289 PhDs, and 148 MDs.

Along with the relatively small size of the graduate programs and faculty, Brown conducts less research than the larger universities. In FY 2021, Brown spent $276 million on research and was ranked 96th in the United States by total R&D expenditure by the National Science Foundation.[28]

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[26] The "Ivy League" refers to a group of 8 private, highly selective universities in the northeastern United States, including Harvard, Yale, Princeton, Columbia, the University of Pennsylvania, Cornell, Dartmouth, and Brown. The Ivy League is an athletic conference – universities whose athletic teams compete against each other – but the term generally is used refer to the group of 8 colleges academically as well.

[27] https://oir.brown.edu/institutional-data

[28] https://ncses.nsf.gov/surveys/higher-education-research-development/2021#data

HISTORY AND CULTURE

Brown has historically been less financially-well-off and less well-known than the other "Ivy League" universities. It has often competed for students by offering a more innovative curriculum.

In 1969, based on student proposals, the university adopted its "open curriculum" which gave students great flexibility in taking courses outside of their concentration (major) and enabled them to design their own majors. It has encouraged interdisciplinary education and increased Brown's popularity among prospective students. The open curriculum allows and supports interdisciplinary education and this culture extends to its graduate school.

Like the other Ivy League universities, Brown is highly selective. In 2022 only five percent of applicants to Brown's bachelor's degree programs were admitted.

Brown has grown gradually but steadily in recent years, with the total number of students growing from 6045 in 1972 to 10,711 in 2022.[29] Much of the growth has been in the graduate programs, which grew from 1357 in 1972 to 2909 in 2022, and in the medical school, which grew from 139 in 1973 to 594 in 2022. Much of the growth has been in master's degree programs.[30]

The historic focus of Brown's graduate programs in most departments has been PhD students. Many Departments only admit students to a PhD program, although some will grant master's degrees on the way to a PhD. Brown guarantees funding for PhD students through research assistantships, teaching assistantships, or fellowships.

The relatively small size of the graduate school facilitates work across departments. The school excels in a few niches (many of which are interdisciplinary) rather than across all fields of science and technology. Most PhDs are awarded through a single department, but some departments are inherently interdisciplinary, such as cognitive science and earth and environmental science.

A program that supports interdisciplinarity among PhD students is the Open Graduate Education Program, which allows select Brown doctoral students to pursue a master's degree in a secondary field. All doctoral students are invited to propose their own combination of studies, free of any disciplinary barrier. The objective of this program is to enable students to

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[29] https://oir.brown.edu/institutional-data/factbooks/historical-student-enrollment

[30] https://oir.brown.edu/institutional-data/factbooks/historical-student-enrollment

combine fields in unique ways and acquire expertise in more than one area. There is no constraint on the choice of the secondary field.

In recent years there has been substantial growth in master's programs at Brown. Master's degrees grew from 15 percent of degrees granted in 2003 to 32 percent in 2023. Over the same time period, bachelor's degrees shrank from 74 percent to 55 percent of degrees. (Percentages of PhDs and MDs stayed about the same.) [31]

The main areas of growth for master's degrees are in field where there are clear job opportunities. Many of these are interdisciplinary. They include programs in biomedical engineering, biotechnology, computer science, data science, innovation management and entrepreneurial engineering, and others.[32]

In 2014, Brown established the School of Professional Studies to provide a focus for flexible programs designed for working professionals to advance their careers without interruption.[33] It offers master's degrees in Healthcare Leadership, Business Administration, and Technology Leadership, as well as shorter (e.g. 4-12 week) non-degree programs in areas such as AI and data science, and innovation leadership.

Master's programs are usually paid for by students and tend to be somewhat less selective than other programs. Brown offers admissions to 42 percent of applicants for master's programs, compared to 5 percent for bachelor's degrees, 3 percent for medical degrees, and 9 percent for doctoral degrees.[34]

EXAMPLES

BROWN SCHOOL OF ENGINEERING

Established in 1847, the Brown engineering program is one of the oldest in the country. In 1916, the departments of civil, mechanical, and electrical engineering were merged into one division of engineering.[35] This model has been preserved and today the School of Engineering is

[31] https://oir.brown.edu/institutional-data/factbooks/degrees-completions

[32] https://oir.brown.edu/institutional-data/factbooks/enrollment

[33] https://professional.brown.edu/degree

[34] https://oir.brown.edu/institutional-data

[35] https://engineering.brown.edu/about/history

organized without the traditional departments or boundaries between engineering disciplines.[36] The school also has many connections throughout the university, such as research with the Department of Neuroscience to develop brain implantable electronic chips and research with archeologists on applying computer vision to reconstruct archeological finds.

Today the engineering school has 409 graduate students, including 168 Ph.D. students, 141 masters of science engineering students, 78 students in the Innovation Management and Entrepreneurship Master's program, and 22 in the Master of Arts in Design Engineering program (an interdisciplinary program conducted jointly with the Rhode Island School of Design). 61 percent of graduate students are international students and 45 percent are women.[37]

PhD students affiliate with one of six research groups: Biomedical Engineering; Chemical and Environmental Engineering; Electrical and Computer Engineering; Fluids and Thermal Sciences; Materials Science and Engineering; and Mechanics of Solids and Structures. Each research area group administers their respective Ph.D. program. Students may use their first year to identify the research group they want to join. Working with an advisor in their research group, PhD students devise a program of study to achieve the breadth and depth of knowledge needed to support their planned dissertation research.

Ph.D. candidates are required to demonstrate proficiency in at least one area outside their main expertise. Minor areas may be other areas of engineering, math, biology, physics, geology or other areas.

BROWN DEPARTMENT OF EARTH, ENVIRONMENTAL, AND PLANETARY SCIENCES (DEEPS)

Geosciences has long been an interdisciplinary field, encompassing geophysics, geochemistry, paleontology, and other areas. DEEPS current areas are Earth History, Environmental Science, Geochemistry, Geophysics, Oceans, Ice and Atmospheres, Planetary Geosciences, Tectonics, Volcanology, and Petrology.[38] DEEPS currently lists 36 faculty and 72 graduate students.

DEEPS accepts students only into its PhD program. Some students may get a master's degree either as a step on the way to their PhD or if they decide to drop out of the PhD program.

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[36] https://engineering.brown.edu/graduate

[37] https://engineering.brown.edu/about/fast-facts

[38] https://deeps.brown.edu/

PhD applicants are encouraged to contact the faculty they are interested in working with before applying, in part to see if the faculty member needs additional students and has the resources to support them. Applicants are also encouraged to visit the department and meet the graduate students associated with the faculty member(s) they'd most like to work with.

All faculty meet early to mid-February to consider all applications. They consider undergraduate courses (including overall GPA, GPA trajectory, and rigor of courses); letters of recommendation; personal statement; and research experience. GRE scores are not considered. The applicant's fit with the needs and interests of specific faculty members is critical. Applicants do not need to have an undergraduate degree in the geosciences, but need to have a relevant background. Some PhD students have undergraduate degrees in related fields (physics, engineering, chemistry, environmental science, etc.)

While most faculty members hold PhDs in some area of geoscience, some have PhDs in other fields (computer science, material science, physics, oceanography) and some have undergraduate degrees in other fields.

BROWN SCHOOL OF PUBLIC HEALTH

Founded in 2013, Brown's School of Public Health is inherently problem-focused and highly interdisciplinary. It was established to improve the health of all populations, through public health scholarship, community partnerships and education. The school has many interactions with the local community, including the Hassenfeld Institute, which is focused on children and families in Rhode Island,[39] as well as partnerships with the state health organizations, community organizations, hospitals, and the Brown medical school.

Research addresses a wide range of topics, including addiction, aging, environmental health, global health, infectious disease, health equity, mindfulness, nutrition and physical activity, statistics and data science, and health care policy, among others.[40]

The school offers undergraduate concentrations, a Master of Public Health (a professional degree), an academic master's, and PhD degrees. Graduate enrollment (Fall 2020) included 100 Master of Public Health students, 51 academic public health master's students, and 80 PhD students.

The School of Public Health is organized in four Departments:

[39] https://hassenfeld.brown.edu/

[40] https://sph.brown.edu/research/areas

- Behavioral & Social Sciences Research
- Biostatistics Research
- Epidemiology Research
- Health Services, Policy & Practice Research

Graduate students come from many backgrounds. There are few requirements but applicants should demonstrate strong quantitative, qualitative, and writing skills (biostatistics grad students have specific math requirements). Applications are evaluated holistically by the admissions committee.

GEORGE MASON UNIVERSITY

BACKGROUND

George Mason University (hereinafter "Mason") is the largest university in the Commonwealth (state) of Virginia, with a total enrollment of nearly 40,000 students, including 26,000 undergraduates and 12,000 graduate and law students.[41]

Mason is a 50-year-old public institution that is owned by the Commonwealth and is overseen by a 16-member board of visitors appointed by the governor of the Commonwealth. It competes directly for public financial and political support with other older and more established public universities in Virginia, including the University of Virginia, the College of William and Mary, Virginia Polytechnic Institute and University, and several others.

Mason has several campuses, including the original campus in Fairfax, the science campus in Manassas, and the Arlington campus, as well as a campus near Inchon in South Korea.[42] It also has several smaller specialized campuses and centers located not only in northern Virginia but throughout the state.

In 2022, Mason reported spending some $220 million on separately budgeted research and development activities (117th rank in the U.S.), including some $120 million on R&D paid for by U.S. Federal agencies and departments (115th rank in the U.S.[43] Mason does not have a medical school, but it is deeply engaged in R&D and advanced education related to health and medicine

[41] https://oiep.gmu.edu/resources/fast-facts/mason-facts-and-figures-2022-2023/

[42] https://www.gmu.edu/about/campuses/locations

[43] https://ncses.nsf.gov/surveys/higher-education-research-development/2022#data

through a variety of departments and research institutes in cooperation with hospitals and medical institutions throughout the region.

HISTORY AND CULTURE[44]

Mason was established to serve the needs of students and employers in the rapidly growing northern Virginia region near Washington DC. Much of the growth in the region during the past several decades has come about because of rapid increases in Federal contracting for research and technical services to serve the needs of key government agencies in defense, space, transportation, health, social services, and information technology. Both Federal agencies and Federal contractors depend on highly educated employees who can conduct problem-focused research or can design and operate advanced technical systems to meet government needs.

Much of the political and community support for establishing Mason came from business leaders who understood the need for a major increase in the supply of well-educated human resources with technical skills, a practical orientation, and an understanding of how to address complex problems in teams and organizations. Thus, Mason has been committed to technology-focused, interdisciplinary education and to research of relevance to society since it was founded in the early 1970s.

Competition for resources from the Commonwealth of Virginia indirectly supported Mason's involvement in interdisciplinary research and education, especially at the graduate level. As noted earlier, Virginia is fortunate to be the home of several distinguished public universities. Through their networks of successful alumni, those institutions have considerable influence over the allocation of public resources to higher education in the State. When Mason was in its early years, the competing institutions worked to limit Mason's reach to undergraduate education in a few fields. Setting up new departments and adding graduate programs in Virginia requires the assent of the powerful agency, the State Council for Higher Education in Virginia (SCHEV). Working through SCHEV and the State legislature, the older universities were able to inhibit the development of graduate and professional education at Mason. Mason's leadership, especially in its critical growth period in the 1980s and 1990s, adopted a strategy of building new graduate and professional programs in interdisciplinary fields that the established institutions did not offer. To house these unusual programs, Mason set up interdisciplinary departments, centers, and institutes that offered educational experiences and graduate

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[44] The material in this section is based on the personal experiences of one of the TPI partners, Christopher Hill, who served George Mason University as a professor in the Institute of Public Policy and the School of Public Policy from 1994 through 2011 and as Vice Provost for Research from 1997 through 2005. For additional information on the history and culture of Mason, see: https://en.wikipedia.org/wiki/George_Mason_University

degrees that combined traditional disciplines in new ways under new labels. Leaders of the various interdisciplinary units were recruited in part based on their demonstrated experience and success in managing such programs. Many of the newly hired faculty members were at the senior levels and were experienced at other institutions or outside higher education in working effectively with other disciplines and across boundaries between academia, industry, government, and the non-profit sector. This hiring strategy tended to remove the challenges of evaluating, promoting, and giving tenure to more junior faculty members within interdisciplinary units that can inhibit the success of interdisciplinary activities at other universities.

Table 5 lists the most prominent of these early interdisciplinary structures at Mason along with some of the disciplines and fields involved in each of them. Because they were created in a somewhat opportunistic fashion, these structures are not homogeneous nor are they equally "interdisciplinary" in character. They represent in part an aggressive, entrepreneurial administration and university leadership taking advantage of opportunities to grow and diversify by identifying groups of outstanding academic leaders who could guide new structures, supported by elements in the surrounding communities who would provide for partnerships, some financial resources, willing collaborations, and opportunities for students. Furthermore, many of these programs offered programs of instruction and research experiences that attracted large numbers of part-time graduate students from the region who were also gainfully employed in the region and could immediately apply their advanced learning to their professional work.

Table 5. Examples of Mason's Interdisciplinary Research and Education Structures During Its Developmental Period 1980-2000

Organizational Unit	**Programs**
Department of Public and International Affairs	Political science Public administration International relations
School of Information Technology & Engineering	Electrical engineering Systems engineering Civil and Environmental engineering Software engineering Applied statistics
Computational Sciences and Engineering Institute	Physics and astronomy Chemistry and materials science Computational sciences Bioinformatics
Institute of Public Policy	Regional economics and development Transportation policy Sociology

	Political science Logistics and operations research Science and technology policy Organization and Knowledge Management Peacekeeping policy
Institute for Educational Transformation	Non-traditional Education
Krasnow Institute for Advanced Research	Microbiology Genetics Astrobiology Complex systems and complexity theory Bioinformatics
Department of Environmental Science and Public Policy	Ecology Aquatic biology Environmental management Climate change modeling and Simulation
Institute for Conflict Analysis and Resolution	Sociology Environmental planning Community development International relations

In the early 1990s, nearly all of Mason's doctoral programs were interdisciplinary in nature except for those in economics, history, psychology, and education. Generally, the interdisciplinary strategy was successful in that it attracted good faculty and graduate students as well as external research funding support and partnerships.

The interdisciplinary approach was not without its detractors and skeptics, however. For, example, at the annual meeting of the entire faculty in 1994, the University president, George Johnson, who had shepherded the university through its interdisciplinary growth, was asked by a faculty member, "When will Mason become a 'regular university'?" Johnson replied, "We are a regular university—a regular university of the future."

By contrast, at the annual meeting of the senior administrators of the University in 1997, the newly-hired president, Alan Merten, observed that "Mason had too many centers and institutes, they overlapped too much, and Mason should eliminate unnecessary organizational units." Merton was much less comfortable than Johnson with the unusual university organization that had evolved at Mason, and he set out to restructure Mason as what one might call a "normal" or even a "regular university."

With continued growth in enrollment, faculty, and research funding and with the focus of faculty hiring shifting from established scholars to newly graduated PhDs, many of the institutes later became "regular" departments or schools, and numerous doctoral degrees were awarded by disciplinary departments.

"Normalization" notwithstanding, the culture of interdisciplinary and problem-focused graduate education and research has remained strong throughout Mason, as the examples in the next section will demonstrate.

EXAMPLES

MASTER OF ARTS IN INTERDISCIPLINARY STUDIES

The Master of Arts in Interdisciplinary Studies program in the College of Humanities & Social Sciences encourages students' freedom and creativity while maintaining the University's commitment to excellence.[45] Founded in 1982, Interdisciplinary Studies recognizes the demand for high quality, non-traditional graduate programs that transcend disciplinary boundaries.

- Multiple established degree paths (concentrations) are offered in partnership with academic units and faculty across the University. They are open to applicants from a range of backgrounds.
- Interdisciplinary Studies offers a home for students with broad academic interests who seek a master's degree that will help them to address critical problems facing the world today, such as environmental degradation, climate change, human trafficking, social injustice, income inequality, trauma and psycho-social healing, gender-based violence, religious intolerance, and international conflict.

DOCTORAL PROGRAM IN BIODEFENSE

The doctoral program in Biodefense is designed to prepare students to serve as scholars and professionals in the fields of biodefense and biosecurity.[46] The program is offered through the Schar School of Policy and Government.

- The program integrates knowledge of natural and man-made biological threats with the skills to develop and analyze policies and strategies for enhancing biosecurity.
- Students study such fields as bacteriology, virology, and toxicity as well as specific areas of biodefense, including nonproliferation, intelligence and threat assessment, and medical and public health preparedness.

COMPUTATIONAL SCIENCES AND INFORMATICS

[45] https://mais.gmu.edu/programs/la-mais-isin

[46] https://schar.gmu.edu/programs/phd-programs/biodefense-phd

The doctoral program in Computational Sciences and Informatics addresses the role of computation in science, mathematics, and engineering through Computer Modeling and Simulation Data Science.[47]

- The program's interdisciplinary approach leads to an understanding that traditional theory and/or experimentation alone cannot provide.
- The close relationship of the PhD to the research and development activities in federal laboratories, scientific institutions, and high-technology firms affords students opportunities for continued or new employment.

EARTH SYSTEMS AND GEOINFORMATION SCIENCES

The Earth Systems and Geoinformation Sciences doctoral program is based on the integration of the scientific disciplines in geosystems, geography, geosciences, and geoinformatics. Students receive broad-based training in systematic geosciences and geography, as well as technical courses in computation and geoinformation sciences.[48]

- The ESGS doctoral program represents a gateway to an academic career for some students; for others, it facilitates career advancement in the public sector or private industry.
- Graduates are equipped to participate in interdisciplinary research, which is the norm in today's research arena.

COMPUTER GAME DESIGN

Finally, to indicate the extent of interdisciplinary research and education at Mason, we mention here the undergraduate degree program in Computer Game Design.[49] This program was begun by faculty members in the College of Art who happened also to have a degree in engineering. He recognized early in the emergence of computer gaming as a big business that there would be a need for university graduates with specialties in gaming and gaming applications, not only for recreation but also for such serious pursuits as war gaming in the national defense world and strategic gaming in firms and institutions. This unusual field is now well-established at Mason and draws on both computer science and the arts.

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[47] https://science.gmu.edu/academics/departments-units/computational-data-sciences/computational-sciences-and-informatics-phd

[48] https://science.gmu.edu/academics/departments-units/geography-geoinformation-science/earth-systems-and-geoinformation

[49] https://game.gmu.edu/

ARIZONA STATE UNIVERSITY (ASU)

BACKGROUND

Arizona State University is a very large state-supported public university in the Phoenix, Arizona metropolitan area (with its largest campus in Tempe). In 2023, it has:

- 112,177 Undergraduate students (79,000 students at 4 Phoenix areas campus, with another 33,000 on-line).
- 30,459 Graduate and professional students
- 5,000+ Faculty members
- 15,100 International students

It is ranked 182 in the Times World University Rankings[50] and 105th in US News and World Report U.S. national universities ranking.[51] It also has also been ranked the most "Most Innovative University" in *U.S. News and World Report* rankings since 2016 (a measure that rates innovation in curriculum, faculty, students, campus life, technology, and facilities). [52]

ASU has a large graduate school and research enterprise, offering 141 PhD degrees and 360 Master's degrees and a variety of online graduate certificates. In 2023 there were 30,459 graduate and professional students.

ASU had $677 million in research expenditures in 2021, ranking 42nd among U.S. universities and 6th among institutions without a medical school.[53] It is noted for many transdisciplinary research centers[54]

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[50] https://www.timeshighereducation.com/world-university-rankings/arizona-state-university-tempe

[51] https://www.usnews.com/best-colleges/arizona-state-university-1081

[52] https://www.usnews.com/best-colleges/rankings/national-universities/innovative

[53] National Science Foundation Higher Education Research and Development (HERD) Survey 2021. https://ncses.nsf.gov/surveys/higher-education-research-development/2021#data

[54] See https://www.asu.edu/academics/centers-and-institutes

HISTORY AND CULTURE

Founded in 1885 as the Territorial Normal School to train teachers for the Arizona Territory (before Arizona became a U.S. state), it became a teachers college in 1925, and became Arizona State University in 1958.[55] It began granting PhDs in 1961 and grew and expanded continuously in both size and academic stature over the next 40 years.

In 2002, the then new president, Michael Crow, committed ASU to become a "new model for the American university."[56] He continues to be ASU president, and his vision has guided ASU for over two decades. This vision is to combine expanding access to education, excellence in research, and social relevance.

In contrast to many research universities (and ranking systems) that equate excellence with selectivity (seeking to admit only the best prepared students) and measure success primarily through research outcomes (e.g., publications and citations), ASU's goal is to seek high quality while **expanding access** (to larger numbers of students, including those from disadvantaged backgrounds) and **emphasizing the social relevance** of the university.[57]

The emphasis on expanding access has led to ASU's large size, as well as use of online education and other innovative instruction methods. The emphasis on social relevance had led to new transdisciplinary programs, departments, and centers focused on socially important problems, as well as many graduate certificate courses focused on specific skills. The emphasis on transdisciplinary work is reflected in new interdisciplinary colleges, schools, and centers, as well as in new programs within more traditional disciplines.

Since 2002, ASU has launched new transdisciplinary colleges, including:[58]

- The College of Global Futures, which offers degrees in sustainability, applied math for life and social sciences; human and social dimensions of science and technology; global development; sustainability, and other topics.

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[55] https://en.wikipedia.org/wiki/Arizona_State_University

[56] Crow, Michael M., and William B. Dabars. "The Emergence of the Fifth Wave in American Higher Education." Issues in Science and Technology 36, no. 3 (Spring 2020): 71–74

Crow, Michael M., and William B. Dabars. "A New Model for the American Research University." Issues in Science and Technology 31, no. 3 (Spring 2015).

[57] https://www.asu.edu/about/charter-mission

[58] https://admission.asu.edu/academics/schools

- The College of Integrative Sciences and Arts, which emphasizes an approach to teaching, learning and discovery that brings many fields of knowledge together to form ideas and solutions.
- The New College of Interdisciplinary Arts and Sciences, which is structured to provide a personal, “small college” learning environment working with faculty across disciplines.

Within more traditionally structured colleges, there are also interdisciplinary programs. For example:

- The Fulton College of Engineering offers degrees in biological design, biomedical engineering, human systems engineering, sustainable engineering among others.
- The College of Liberal Arts and Science is mostly structured in traditional disciplines, but has many interdisciplinary programs, including computational life sciences, exploration systems design, and global health.

Graduate admission decisions are decentralized. While ASU has minimum requirements for admission to master's, certificate, and doctoral programs (typically requiring a bachelor’s degree and B-average grades), each ASU graduate program has unique admission standards.[59] Masters and (especially) graduate certificate programs provide great flexibility to be responsive to workforce and social needs. PhD programs tend to be more rooted in traditional disciplines, but some are in interdisciplinary areas.

While ASU highlights its new model, with emphasis on inclusivity and social relevance, many other public universities share similar goals and characteristics. Many other large state universities also seek to educate large numbers of students and seek to be relevant to their state’s economic and workforce needs. While ASU’s efforts to expand and to admit more students make it less selective than some universities, it is still selective. And like other research universities, ASU faculty compete nationally for research funding and are selected and evaluated on their success in getting funding and publications. Similarly, many of ASU PhD’s are still granted within traditional disciplines.

[59] https://admission.asu.edu/apply/graduate/admission

EXAMPLES

ASU COLLEGE OF GLOBAL FUTURES

Part of the Julie Ann Wrigley Global Futures Laboratory, the College of Global Futures is "the world's first comprehensive, university-based approach to ensuring a habitable planet and a future where well-being is attainable for all humankind."[60] It contains four schools:

- School for the Future of Innovation in Society
- School of Sustainability
- School of Complex Adaptive Systems
- School of Ocean Futures (this is new, and expects to have its first programs in 2024-25)

It offers Masters, PhD, and graduate certificate programs related to sustainability, global development, complex systems, human and social dimensions of science and technology; and others.

INTERDISCIPLINARY PROGRAMS IN TRADITIONAL COLLEGES

The Fulton School of Engineering offers PhD and MS programs in both traditional engineering fields (e.g., electrical, civil, chemical) and many transdisciplinary fields (e.g., biological design, human systems engineering).[61] It has more than 30 research centers which are often interdisciplinary (such as environmental biotechnology, complex systems safety, and algae technology and innovation).[62]

The College of Liberal Arts and Science describes itself as the academic heart of ASU. [63] It is home to many traditional disciplines in the sciences, social sciences, and languages, but also includes many interdisciplinary programs. Master's and PhD programs are both in traditional disciplines as well as interdisciplinary areas such as exploration systems design, and environmental social science.[64] There are also many graduate certificate programs in

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[60] https://collegeofglobalfutures.asu.edu/

[61] https://graduate.engineering.asu.edu/

[62] https://research.engineering.asu.edu/research-centers/

[63] https://thecollege.asu.edu/

[64] https://thecollege.asu.edu/degrees/graduate

interdisciplinary areas related to social needs or emerging opportunities (e.g. digital humanities, immigration studies, museum studies, socio-economic justice).

UNIVERSITY OF CALIFORNIA BERKELEY

BACKGROUND

The University of California, Berkeley, is a public university created in 1868 by the State of California. UC Berkeley (also known as "Cal" or "UCB") is often ranked as the top public university in the United States.[65] In the Fall of 2022, Berkeley had 45,600 students – 33,078 undergraduates and 12,621 graduate and professional students.[66]

Berkeley is very strong in STEM fields, including physics, chemistry, engineering, computer science, and biology. Total research spending (from both public and private sources) in 2022 was $981,166,000. That year Berkeley ranked 32nd among U.S. universities in terms of total R&D spending. Of this total amount, $468,542,000 came from federal agencies, making Berkeley the 33rd highest ranking campus in terms of federal support.[67] The reason that Berkeley does not rank higher among universities in terms of R&D funding is that, unlike many other highly-ranked U.S. universities, Berkeley does not have a medical school. (The main medical center for the University of California system is UC San Francisco, a campus with which UCB faculty and students often collaborate.)

Berkeley has long played an important role in U.S. science and technology. Perhaps most importantly, UCB and its professors were instrumental in the creation of three national laboratories: Los Alamos National Laboratory, Lawerence Berkeley National Laboratory, and Lawrence Livermore National Laboratory – the last two named for Berkeley physics professor Ernest Orlando Lawrence. While the Los Alamos and Livermore laboratories are not located near the UC Berkeley campus, the University of California still manages them (with partners).

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[65] See, for example, Ivan Natividad, "UC Berkeley No. 1 U.S. public university in Times Higher Ed rankings," *Berkeley News*, September 17, 2023, https://news.berkeley.edu/2023/09/27/uc-berkeley-no-1-u-s-public-9th-best-globally-in-2024-times-higher-ed-rankings

[66] "UC Berkeley Quick Facts," https://opa.berkeley.edu/campus-data/uc-berkeley-quick-facts.

[67] National Science Foundation, "Table 21: Higher education R&D expenditures, ranked by FY 2022 R&D expenditures: FYs 2010-22" and "Table 24: Federally financed higher education R&D expenditures, ranked by 2022 R&D expenditures: FYs 2010-22," both tables available at: https://ncses.nsf.gov/surveys/higher-education-research-development/2022#data.

Lawrence Berkeley is located in the hills immediately above the campus – which has facilitated close collaborations between the two institutions.

As a public university, Berkeley has many programs that directly or indirectly support California's state government and California industry. Overall, it has a culture that emphasizes research excellence, public service, and entrepreneurship

HISTORY AND CULTURE

In 1862, during the U.S. Civil War, Congress passed and President Lincoln signed the Morill Act, a law that provided federal land to state government for the purpose of creating universities of agriculture and mechanics. States could use some of the land for the universities and sell the remainder to pay for university operations. In 1868, California's government created the University of California as a land-grant institution. The school opened in 1869 in Oakland, California, and it soon moved to a new site just north of Oakland. An official suggested naming the campus in honor of the Anglo-Irish Philosopher George Berkeley. The university began with only male students but admitted its first women students in 1870.[68]

The campus initially had an agriculture school, as part of its land-grant responsibilities. In 1905, a University Farm was established near Sacramento, ultimately becoming the University of California, Davis. Another major step occurred in the 1930s, when Berkeley physicist Ernest Lawence established the Radiation Laboratory (now Lawrence Berkeley National Laboratory, also called "Berkeley Lab") and invented the cyclotron, an early particle accelerator. Using this cyclotron and related machines, UC Berkeley professors and Berkeley Lab researchers discovered 16 chemical elements – more than any other university in the world. In 1942 Berkeley physics professor J. Robert Oppenheimer became the scientific director of the Manhattan Project.[69]

In the 1960s, UC Berkeley became a center for political activism. The Free Speech Movement of 1964 protested restrictions on students' political activities, and later many people on the campus protested the Vietnam War.

In the 1980s and later, Berkeley strengthened its programs in research and STEM education. In the 1980s it established an important Mathematical Sciences Research Institute. The campus has long been a leader in electrical engineering and computer science, and in 2001 the State of California expanded its these programs by establishing a Center for Information Technology Research in the Interest of Society (CITRIS). The campus also has the Simons Institute for the

[68] "University of California, Berkeley," *Wikipedia*, https://en.wikipedia.org/wiki/University_of_California,_Berkeley.
[69] Ibid.

Theory of Computing and in 2022 Berkeley created a new College of Computing, Data Science, and Society. While Berkeley does not have its own medical school, it is very strong in life sciences research. In recent years, the campus established the Energy Biosciences Institute, the California Institute for Quantitative Biosciences, and the Innovative Genomics Institute (in partnership with UC San Francisco). Berkeley remains very strong in biosciences. For example, Jennifer Doudna, who shared a Nobel Prize for her work on CRISPR gene editing technologies, is a Berkeley professor.

It is hard to precisely define the culture of any university, but based on scholarly studies and the TPI team's own observations, we can make a few points.

First, from its beginning Berkeley has emphasized research excellence. In its earliest days, Berkeley emulated Johns Hopkins University, a school that emphasized research and, following Germany, established some of the earliest formal PhD programs in the United States. Beginning in the 1890s, Berkeley offered research support to its professors, helping the campus to recruit outstanding young scientists.[70]

Second, Berkeley has a reputation for hiring world-class researchers who are often fiercely independent. However, Berkeley professors often share common interests and will voluntarily work together. TPI's observation is that interdisciplinary cooperation at Berkeley is often "bottom-up," resulting from the interests of the faculty rather than imposed from "above" by university administrators or California state officials.

Third, public universities, including Berkeley, have a reputation for being highly "bureaucratic" – that is, bound by many rules and slow to change. It is true that professors within public universities must not only follow their campuses' own internal rules; they must also follow rules and budget restrictions imposed by their state governments. However, Berkeley has a long tradition of being relatively independent of the state government, and professors and academic leaders have found ways to create interdisciplinary research centers and interdisciplinary PhD programs. Some examples of these programs are discussed below.

EXAMPLES

ENERGY AND RESOURCES GROUP

[70] Martin Kenney, "A Tale of Two Universities: Entrepreneurship in the Departments of Electrical Engineering and Computer Science at UC Berkeley and Stanford," Berkeley Roundtable on the International Economy, January 3, 2003.

Berkeley's Energy and Resources Group (ERG) is an interdisciplinary research and education program, created in the early 1970s. It combines research on energy technologies with ecology, economics, and policy.

ERG was a pioneering organization on campus: the first interdisciplinary program to have its own tenured faculty member. Until then, only faculty in regular academic departments could receive tenure. The first ERG professor to receive tenure was John Holdren, later President Obama's science and technology advisor.

ERG's website summarizes its history:

> ERG traces its origins to the Committee on Energy and Resources, which was established in November 1972…. The Committee laid the groundwork for an interdisciplinary program of teaching and research in energy and resources and secured for this purpose the first regular faculty position in Berkeley's history to reside entirely in an interdisciplinary unit. John P. Holdren (emeritus) was appointed to fill that position, as Assistant Professor in the Energy and Resources Program, in summer 1973. The program attained degree-granting status as a Graduate Group in late 1974, and admitted its first graduate students in 1975.[71]

The ERG website also refers to one important feature of Berkeley: the ability of faculty and students to learn from other professors in other parts of this large university. While most graduate students remain within established academic departments, they have the freedom to take classes in a very wide range of disciplines. Many graduate students ask professors from other departments to serve on their PhD committees. And students at Berkeley can pursue "joint degrees" in which they get a second academic degree, as illustrated by the options available to ERG graduate students.

> The Berkeley Campus offers exceptional opportunities to learn from outstanding scholars in many disciplines. ERG facilitates the placement of specialized knowledge into the larger integrated perspective. Students and faculty incorporating one another's insights, work on alternative energy technologies, ecological economics, terrestrial ecology, environmental justice, resource conflicts, and society and technology….
>
> ERG's programs include:
>
> - Ph.D. (Doctor of Philosophy in Energy and Resources)

[71] Berkeley Energy and Resources Group, "About ERG," https://erg.berkeley.edu/about/

- Master's Degree (2-year M.S. or M.A. in Energy and Resources)
- Concurrent ERG/Public Policy Master's Degree (3-year M.P.P and M.S. or M.A. in Energy and Resources)
- Concurrent ERG Master's/Law J.D. Degree
- Undergraduate Minor in Energy and Resources
- Sustainability Summer Minor/Certificate

One problem that interdisciplinary programs face is where they should be located within a university. For example, should a program such as ERG be in a university's engineering school, a humanities and sciences school, a policy school, or elsewhere? Stable funding can also be a problem for these programs, if no major part of the university wants to support them.

In the case of ERG, it is now located administratively within Berkeley's College of Natural Resources, which is the current name for what originally was the College of Agriculture.

DEPARTMENT OF ENVIRONMENTAL SCIENCE, POLICY, AND MANAGEMENT

This department focuses on ecology and environmental management and is also located within the College of Natural Resources. The department's PhD program combines an emphasis on a core discipline with a broad interdisciplinary education (including the social sciences) and with exposure to cross-disciplinary communication and problem solving.[72]

LIFE SCIENCE REORGANIZATION

In the early 1990s, Berkeley renovated its large life sciences building (the Valley Life Science Building) and at the same time consolidated several old departments (such as Paleontology, Botany, and Zoology) into a new Department of Integrative Biology. Creating one large department allowed professors and students who were previously in different departments to work together more easily. The renovation of the building also created new state-of-the-art research laboratories that made interdisciplinary research easier.[73]

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[72] Department of Environmental Science, Policy, and Management, "ESPM's History," https://ourenvironment.berkeley.edu/about/history.

[73] Biosciences Divisional Services, "VLSB History," http://bds.berkeley.edu/vlsb/history.

Other biology programs were combined into a new Department of Molecular and Cell Biology. Here, too, combining many life sciences disciplines into a single department reduced barriers to cooperation and facilitated trans-disciplinary research and education

COLLEGE OF COMPUTING, DATA SCIENCE, AND SOCIETY

Established on July 1, 2023, this is the first new college at Berkeley in over 50 years. It offers both undergraduates and graduate students opportunities to work on interdisciplinary topics within data science. The new school offers PhD degrees in computational biology, computational precision health, electrical engineering and computer sciences, and statistics. As part of the interdisciplinary nature of these PhD programs, computational biology students work closely with geneticists, and computational precision health students often work with specialists at UC San Francisco.

The new School emphasizes work on societal challenges. The website explains: "Innovations in computing and statistics are converging to created unprecedented opportunities to use data science, machine learning, and artificial intelligence to tackle pressing societal challenges from human health to climate change."[74]

THE BUSINESS SCHOOL'S INSTITUTE FOR BUSINESS INNOVATION

Berkeley's Haas School of Business has an Institute for Business Innovation. This Institute does not grant its own degrees, but it brings together faculty and students from both the Business School and other parts of Berkeley to work together. A typical course on entrepreneurship will include business students, engineering students, and others working in teams to identify business opportunities. Other courses teach students about design thinking and applied innovation. Faculty and students also study the innovation process and organize conferences and seminars to examine innovation and disseminate new research on innovation.[75]

UC BERKELEY AND LAWRENCE BERKELEY NATIONAL LABORATORY (LBNL)

Lawrence Berkeley National Laboratory (LBNL or "Berkeley Lab") is a Department of Energy laboratory, managed by the University of California, that conducts interdisciplinary research in the physical sciences and clean energy. It has six major research areas: bioscience, computing science, earth and environmental sciences, energy sciences, energy technologies, and physical

[74] Berkeley College of Computing, Data Science, and Society, "Student Resources and Information," https://data.berkeley.edu/information-and-resources-students.

[75] Berkeley Haas, "Institute for Business Innovation," https://haas.berkeley.edu/ibi/.

sciences. The lab operates five major National User Facilities, which are research instruments used by LBNL scientists, university researchers, and companies.[76]

As mentioned earlier, Berkeley physicist Ernest Lawrence created the laboratory (then called the Radiation Laboratory). He created it in 1931, using money from private foundations. After World War II, it became a laboratory of the Atomic Energy Commission (now the U.S. Department of Energy).[77]

Because the University of California manages LBNL and because the Lab is located next to the UC Berkeley campus, there is a long tradition of collaboration between the campus and the Lab. Much of this research and education is interdisciplinary. Currently:

- 242 researchers hold both UC Berkeley faculty positions and LBNL positions
- 416 UC graduate and undergraduate students participate in research projects at the Lab
- 1,946 UC researchers use Lab facilities[78]

MAIN STUDY TOPICS

Following the broad comparison of undergraduate and graduate programs, and the discussion of the 6 case institutions, we now turn to the main topics of the report:

- What incentive structures and external conditions encourage or discourage diversity and boundary-spanning in U.S. graduate education?
- How do graduate programs affect the opportunities for graduate students to learn or apply trans-disciplinary skills to address complex social problems?

INCENTIVE STRUCTURES AND EXTERNAL CONDITIONS THAT ENCOURAGE/DISCOURAGE DIVERSITY AND BOUNDARY-CROSSING

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[76] Berkeley Lab's home page is: https://www.lbl.gov/.

[77] "Lawrence Berkeley National Laboratory," *Wikipedia,* https://en.wikipedia.org/wiki/Lawrence_Berkeley_National_Laboratory#From_1946_to_1972:_discovering_the_antiproton_and_new_elements.

[78] Berkeley Lab, "Berkeley Lab and the University of California," https://www.lbl.gov/about/university-of-california/.

The main elements of the incentive structures and external conditions that encourage or discourage diversity and boundary-spanning in U.S. graduate education include:

- The role of competition for research funding, faculty, and students
- The roles of external stakeholders
- How student recruitment and admissions processes affect the admission of students to graduate programs and encourage or discourage boundary crossing as well as the diversity of incoming student backgrounds.

THE ROLE OF COMPETITION FOR RESEARCH FUNDING, FACULTY AND STUDENTS

A standard view of the goal of U.S. research universities is that they seek to accumulate the highest level and greatest amount of internal academic quality, consisting of research-productive faculty, high quality students, and the best environment.[79] Universities seek to maximize revenue to purchase quality (through attracting high quality faculty, researchers, and students, and improving research facilities), and then use the quality to attract more external funds, such as research grants and philanthropic gifts. The U.S. system is characterized by competition in all of these areas. Universities compete for funding, faculty, and students, and faculty and students also compete for positions in the best universities. Within this environment, there are elements that both encourage and discourage interdisciplinary graduate education.

A major force encouraging interdisciplinary education is the recognition by the research community of the importance of interdisciplinary research. This recognition has taken the form of many workshops and reports emphasizing the need for interdisciplinary work.[80]

Many new and emerging fields of science and technology are interdisciplinary. In addition, efforts to increase societal benefit from research, through working on important problems or working with industry, tend to support interdisciplinary work. Most important industrial or social problems require interdisciplinary research.

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[79] John V. Lombardi. *How Universities Work*. Baltimore: Johns Hopkins Press 2013

[80] See for examples National Academies. *Facilitating Interdisciplinary Research* Washington: National Academies Press. 2005. Also National Academies. *Convergence: Facilitating Transdisciplinary Integration of Life Science, Physical Science, Engineering, and Beyond*. Washington: National Academies Press. 2014.

As the research community recognizes the value of interdisciplinary work, research agencies and foundations create interdisciplinary funding opportunities. Universities seek to win these funds. To win these funds, universities need to have high quality faculty interested in interdisciplinary work as well as appropriate research facilities. Faculty members who see opportunities for funding and publications in these areas write proposals and win grants to work in these areas, and then can support students to do interdisciplinary research.

The U.S. system, however, also has some substantial disincentives for interdisciplinary research and education. Some funding agencies and their peer review committees that shape research funding decisions (for example many of those at the National Science Foundation and National Institutes of Health) are organized by disciplines. These tend to resist or undervalue interdisciplinary work.

University departments are also largely structured along disciplines. They tend to make promotion and tenure decisions based on contributions to the discipline and have a more difficult time evaluating the quality of interdisciplinary work. In addition, the "quality" of a faculty member may be measured in part by the quality of their publications, and many of the oldest and most prestigious journals are disciplinary; new interdisciplinary fields take time to establish high-reputation journals.

Graduate students seeking academic careers and untenured professors are often advised to focus on disciplinary work until they get tenure, which may be 5 to 15 years into their research career, at which time it may be harder for them to change research direction. Graduate students who seek non-academic jobs in industry or government, however, are freer to pursue interdisciplinary education.

The conflict between these incentives and disincentives are reflected in the case institutions. While many new research centers at the case institutions are interdisciplinary, most PhD students are associated with traditional disciplinary programs.

THE ROLES OF EXTERNAL STAKEHOLDERS

As suggested by the discussion above, external stakeholders exert a significant influence on interdisciplinary and problem-oriented graduate education. Different stakeholders have different influences.

Research Funding Agencies have varying influences. Some agency programs support science through disciplinary programs. These include most of the National Science Foundation (NSF), much of the National Institutes of Health (NIH), and some of the Department of Energy (DOE) and Department of Defense (DOD) R&D programs. These often reinforce the disciplinary structure in universities. Other Federal agency programs support problem-oriented research that tends to be interdisciplinary. These include some NSF and NIH programs and centers, as well as many of the programs in DOE, DOD and NASA.

Private Foundations vary greatly in their goals and research programs, but often support research directed at societal need or goals, and much of this work is interdisciplinary. Private foundations often provide funds to universities that are used for interdisciplinary research centers.

Industry typically supports problem-oriented research (often in partnership with government funding). Companies often want to hire students with enough breadth to work on industrial problems. They provide career opportunities for graduate students with interdisciplinary education.

The U.S. Congress, which provides the funding for Federal R&D agencies, generally wants public benefit from research, which often encourages interdisciplinary work. Some members of Congress, however, may oppose applied research that benefits industry or addresses social problems.

State governments and boards of regents have a variety of goals. They often want state universities to provide economic benefits and a skilled workforce for their state, which often requires interdisciplinary programs. But some may support traditional education and be opposed to new interdisciplinary programs.

HOW STUDENT RECRUITMENT/ADMISSIONS AFFECTS BOUNDARY SPANNING AND STUDENT DIVERSITY

A variety of features of the recruitment/admissions process affect boundary spanning and student diversity.

As discussed in the previous report,[81] the U.S. system lets students specialize at a later time than many other systems – students frequently change majors during their undergraduate education and can pursue a graduate degree in different fields from their undergraduate degrees. Most graduate programs do not require students to have undergraduate degrees in the same field (but they generally do require evidence of having coursework or work

[81] David W. Cheney, Christopher T. Hill, and Patrick H. Windham. Cross-Disciplinary Education in U.S. Colleges and Universities, Part I: Undergraduate Students. A Report to JST. Technology Policy International. March 2023.

experience that provides an adequate background for the graduate work). Interdisciplinary graduate programs also generally require students to demonstrate preparation for and interest in the subject of the program, but most programs welcome students with diverse backgrounds.

Another source of student diversity is that most universities encourage their undergraduates to go to a different school for PhD work, and most PhD programs seek students with bachelor's degrees from other universities. This is a general practice rather than a rule or policy, and exceptions are often made in individual cases, but the general idea in the U.S. is that students benefit by being pushed outside of their comfort zone, by getting more diverse views of their field, and by making broader connections.[82]

Another source of diversity in background in U.S. graduate programs is the high number of foreign students. In 2021, 34.1 percent of U.S. science and engineering master's degrees and 34.8 percent of PhD degrees were awarded to international students on temporary visas.[83] With some exceptions for national security related programs, most graduate programs welcome foreign PhD students and provide support for these students through teaching assistantships and research assistantships, just as for U.S. students. (Some U.S. government graduate fellowships are only available for U.S. citizens or permanent residents). Finally, most universities (and many public policies) seek to encourage greater participation by under-represented ethnic or racial groups in education.

All these features result in U.S. graduate schools having students with diverse intellectual and cultural backgrounds.

HOW GRADUATE PROGRAMS AFFECT OPPORTUNITIES FOR GRADUATE STUDENTS TO LEARN/APPLY INTERDISCIPLINARY SKILLS TO ADDRESS COMPLEX SOCIAL PROBLEMS

This section addresses the follow questions:

- How is interdisciplinarity driven by research opportunities and faculty interest under the linkage of graduate education and research?
- To what extent is learning design based on individual student experiences and needs?

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[82] For a discussion of this issue, see: https://chemjobber.blogspot.com/2013/01/bs-and-phd-at-same-institution.html

[83] National Science Board. *Science and Engineering Indicators. Higher Education in Science and Engineering.* https://ncses.nsf.gov/pubs/nsb202332/characteristics-of-s-e-degree-recipients#international-students-in-u-s-s-e-higher-education

- To what extent does the U.S. system help researchers develop skills such as scientific writing, cross-disciplinary and cross-institutional project management, data management, presentation, international collaboration, and conference organization and management?
- What are opportunities for collaborations with companies or communities, opportunities for education and research to respond to social needs, and opportunities for students and faculty to be exposed to social issues and to meet people from different standpoints?

INTERDISCIPLINARITY DRIVEN BY RESEARCH OPPORTUNITIES AND FACULTY INTEREST UNDER THE LINKAGE OF GRADUATE EDUCATION AND RESEARCH

As discussed earlier, there is a strong linkage between interdisciplinary research opportunities, faculty interests, and interdisciplinary graduate education and research. Interdisciplinary funding opportunities encourage faculty to pursue interdisciplinary research. At the same time, faculty interest in interdisciplinary research can drive interdisciplinary funding opportunities as priorities from the research community (often expressed through workshops and advisory panels) shape funding research programs at Federal agencies. Faculty interest in interdisciplinary research, in turn, drives interdisciplinary graduate education, since faculty with interdisciplinary research funding will be able support and train graduate (typically PhD) students who have interdisciplinary interests.

The main U.S. R&D funding agencies all support some interdisciplinary work at universities and all are aware of the importance of university research in training graduate students. The National Institutes of Health, the Department of Defense, and the National Science Foundation are the three largest funders of U.S. academic research.[84] Each has had substantial programs to expand interdisciplinary research. The NSF is a good example. It is the U.S. agency with the broadest and most explicit mission to invest in university research and to strengthen graduate education. While NSF is organized around disciplines and is the main source of disciplinary research funding, it has undertaken many efforts to support interdisciplinary research and what it calls "convergence research," which is problem-driven research that brings together people from different disciplines.[85] It offers many different funding opportunities, many of which are

[84] See National Science Board. "Academic R&D." *Science and Engineering Indicators*. October 2023. https://ncses.nsf.gov/pubs/nsb202326/funding-sources-of-academic-r-d

[85] See: https://new.nsf.gov/funding/learn/research-types/learn-about-interdisciplinary-research and https://new.nsf.gov/funding/learn/research-types/learn-about-convergence-research

interdisciplinary.[86] It quite common for faculty from different areas to work together in ad hoc teams for specific projects with participation by students from different fields. NSF also supports interdisciplinary research through its support of centers. The Engineering Research Centers program and the Industry-University Cooperative Research Centers are examples of interdisciplinary centers that NSF supports.[87] New interdisciplinary research centers often grow out of ad hoc arrangements.

Other research agencies also have specific programs to support interdisciplinary research at universities, in addition to supporting interdisciplinary work through normal grants.[88] In addition, many national multi-agency science and technology initiatives, such as those on manufacturing, artificial intelligence, and quantum information science, are highly interdisciplinary and support many centers that have both research and education missions.[89]

At universities, as illustrated in the case institutions, interdisciplinary research and graduate education may be conducted through the departments (such as engineering at Brown) or may lead to new organizations (such as Bio-X at Stanford or the Media Lab at MIT).

LEARNING DESIGN BASED ON INDIVIDUAL STUDENT EXPERIENCES AND NEEDS.

While there is a wide variation among graduate programs, the following are some generalities about individual customization in U.S. graduate education.

Master's degree programs tend to have somewhat standardized coursework, but students generally have some elective courses that they can choose to fit their interests. Depending on the program, these may be in their department or outside their department. Many MS degrees also require a thesis or capstone project that requires individualized learning or research, usually under the guidance of a professor.

[86] See https://new.nsf.gov/funding/opportunities for a list of NSF funding opportunities.

[87] Information on the Engineering Research Centers is at https://www.nsf.gov/eng/eec/erc.jsp ; information on the industry-university cooperative research centers is at https://iucrc.nsf.gov .

[88] An example at the National Institutes of Health is https://commonfund.nih.gov/Interdisciplinary . An example at the Department of Defense is https://www.defense.gov/News/Releases/Release/Article/2953234/department-of-defense-announces-university-research-funding-awards/

[89] See, for example, the list of NSF supported quantum information centers at https://www.nsf.gov/mps/quantum/quantum_research_at_nsf.jsp

PhD coursework and research have long been highly individualized. Students typically take some required basic coursework. Students often take some additional courses on an individual basis to make up for any deficiencies in their background that are needed to pass qualifying exams. Students may take an additional customized set of courses to prepare for their dissertation topic. Again, these courses may be in their home department or elsewhere. The more interdisciplinary the research is, the more likely the need to take courses in other departments. Some universities (such as MIT and Berkeley) enable students to form customized interdisciplinary PhDs. The dissertation research itself leads to highly individualized learning, with many variations across institutions and disciplines.

RESEARCHER DEVELOPMENT PRACTICES AND OTHER APPROACHES TO EMPOWER RESEARCHERS WITH TRANSFERABLE SKILLS.

Graduate students may learn a variety of skills, such as those useful for scientific writing, cross-disciplinary and cross-institutional project management, data management, presentations, international collaboration, and conference organization and management. These tend to be taught in ad hoc ways that vary substantially across institutions and programs.

Many universities have writing centers that can assist students with writing. Project management skills are usually not taught formally but may be learned from a faculty mentor/advisor. Students are more likely to gain project management skills when they are involved in large projects, where some graduate students may become involved in project management.

Data management, presentation skills, international collaboration, conference organization and management all vary substantially. They are rarely taught through formal programs, although some universities may have short training programs available. The skills are typically learned by graduate students if the advisor/mentor is strong in the topic, or if their project requires skills in the area. For example, if a faculty member is organizing a conference or engaged in international collaboration, his or her graduate students are likely to learn associated skills.

OPPORTUNITIES FOR COLLABORATION WITH COMPANIES OR COMMUNITIES; OPPORTUNITIES FOR EDUCATION AND RESEARCH TO RESPOND TO SOCIAL NEEDS; AND OPPORTUNITIES FOR STUDENTS AND FACULTY TO BE EXPOSED TO SOCIAL ISSUES AND TO MEET PEOPLE FROM DIFFERENT STANDPOINTS

There is wide variation across types of programs with respect to these practices.

Most engineering and some science programs have strong collaborations with industry. Collaborations with industry tend to focus on industrially-relevant problems and opportunities that do not follow disciplinary boundaries and tend to require interdisciplinary solutions.

Graduate programs respond to social needs through several mechanisms. Research funding opportunities, both from government agencies and private foundations, are often focused on social needs, and these lead both faculty and PhD students to focus their work in these areas. At the master's level, student interest and perceived employment opportunities encourage the development of interdisciplinary programs focused on social needs.

Some graduate programs (such as those in public health, economics, environmental science, public policy, psychology, anthropology) frequently involve social issues and often include interaction with their local communities. Brown's School of Public Health, which has many interactions with the State of Rhode Island, is a good example. On the other hand, universities have long been criticized for contributing too little to their surrounding communities (sometimes termed "town and gown conflicts").[90] Many universities today (such as Arizona State and George Mason) make deliberate efforts to be involved with their local communities.

As described earlier, U.S. graduate schools tend to admit people from a variety of intellectual, geographical, and cultural backgrounds. This includes the large number of international students (and faculty members). There are also a wide variety of national policies and cultural pressures to expand participation of underrepresented minorities and disadvantaged students in graduate education. There are Federal- and foundation-funded graduate fellowships for underrepresented groups, and many universities recognize a responsibility to increase participation from underrepresented groups.

OBSERVATIONS AND CONCLUSIONS

Most science and engineering PhD programs at major U.S. research universities continue to be located in departments based on traditional science and engineering disciplines. Most faculty members prefer to work in traditional departments, and students often have an easier time finding an academic job if they have a PhD degree in a traditional science or engineering discipline.

At most universities, discipline-based departments are the dominant organizational structure and control most hiring and promotion of faculty. It is still generally believed to be easier to achieve tenure in most departments based on disciplinary rather than interdisciplinary work.

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[90] Wikipedia. "Town and gown." https://en.wikipedia.org/wiki/Town_and_gown

Many interdisciplinary efforts are led by faculty who are tenured (and thus more able to take risks).

However, U.S. universities have incentives to work in boundary-spanning areas and the organizational flexibility to do so.

First, professors and graduate students often want to work on the most exciting research questions, and often these questions are trans-disciplinary. These exciting questions may be related to social issues (such as climate change) or they may arise in very basic research (such as using new technologies to study the early history of the universe). Universities that compete for the best professors and students encourage these professors and students to work on these trans-disciplinary topics.

Second, and related, U.S. academic disciplines themselves often change; either new disciplines and departments emerge (such as materials science and engineering, computer science, and bioengineering) or sub-specialties emerge within traditional departments (such as bioinformatics and computational biology emerging as part of traditional life sciences departments).

Third, even if professors and their graduate students are formally based in traditional academic departments, they can collaborate with colleagues or even create new centers, institutes, or programs that allow additional boundary-spanning work. For example, graduate students can take courses in other departments, and may have professors from multiple departments on their PhD thesis committees.

Federal R&D agencies in the U.S. sometimes hinder and sometimes help the efforts of professors and graduate students to do trans-disciplinary research and education. For example, the National Science Foundation (NSF) is itself organized primarily by academic disciplines, and its science divisions have sometimes struggled to fund trans-disciplinary research. However, it has made efforts to expand interdisciplinary funding opportunities throughout NSF, and some parts of NSF, such as the Engineering and Computer Directorates have long funded interdisciplinary centers and projects.

Other R&D funding agencies (NIH, DOE, NASA, DOD) fund a mix of disciplinary science and more problem-oriented research that tends to be interdisciplinary. The Defense Advanced Research Projects Agency (DARPA) and similar "ARPA" agencies in other departments often fund multi-disciplinary teams that focus on developing new advanced technologies and capabilities. National research initiatives (such those in artificial intelligence, quantum information science, manufacturing, and climate) also tend to be highly interdisciplinary.

The overall picture at leading U.S. research universities is therefore a mix of traditional academic departments, based on traditional science and engineering disciplines, combined with new disciplines and departments, informal collaborations, new trans-disciplinary research centers, and sometimes new multi-disciplinary PhD programs (such as bioengineering or bioinformatics). In the competitive U.S. research environment, universities have the incentive and ability to constantly adjust their graduate programs to reflect the new interests of faculty, graduate students, and funders. The cases discussed in this report illustrate these features of U.S. higher education.