Thomas R. Cech

Science at Liberal Arts Colleges: A Better Education?

IT WAS THE SUMMER OF 1970. Carol and I had spent four years at Grinnell College, located in the somnolent farming community of Grinnell, Iowa. Now, newly married, we drove westward, where we would enter the graduate program in chemistry at the University of California, Berkeley. How would our liberal arts education serve us in the Ph.D. program of one of the world's great research universities? As we met our new classmates, one of our preconceptions quickly dissipated: Berkeley graduate students were not only university graduates. They also hailed from a diverse collection of colleges—many of them less known than Grinnell. And as we took our qualifying examinations and struggled with quantum mechanics problem sets, any residual apprehension about the quality of our undergraduate training evaporated. Through some combination of what our professors had taught us and our own hard work, we were well prepared for science at the research university level.

I have used this personal anecdote to draw the reader's interest, but not only to that end; it is also a "truth in advertising" disclaimer. I am a confessed enthusiast and supporter of the small, selective liberal arts colleges. My pulse quickens when I see students from Carleton, Haverford, and Williams who have applied to our Ph.D. program. I serve on the board of trustees of Grinnell College. On the other hand, I teach undergraduates both in the classroom and in my research laboratory at the University of Colorado, so I also have personal experience with science education at a research university.

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Thus, recognizing that I may be too close to this subject to be completely unbiased, I have attempted to broaden my view in several ways. I have gathered statistics that quantify some aspects of the success of science education in liberal arts colleges versus research universities, although interpretation of these numbers is not unambiguous. I have also interviewed scientists who have achieved the highest levels of success in academia and government to obtain their perspective on the relative strengths and weaknesses of the preparation afforded by liberal arts colleges. I did so knowing that those interviewed had excelled in their profession, so one would expect them to be generally enthusiastic about the education that had preceded their success. Finally, I have sought the counsel of some of the country's best college science teacher-scholars, those who are truly immersed in the subject. Others who have analyzed the subject of science education at liberal arts colleges have independently come to similar conclusions, providing some confidence that this shared view must not be too far off the mark.[1]

The aim of this essay is to explore three questions regarding undergraduate science education. First, how successful are those graduating from liberal arts colleges compared to their contemporaries at large universities? This analysis is based on objective measures of success, including the percentage of graduates who go on to obtain Ph.D. degrees. Second, how does the education at liberal arts colleges compare with that encountered by undergraduates at large universities? Both classroom education and research experiences will be considered. Third, why are the top liberal arts colleges so successful in training successful scientists? Here we confront a vexing conundrum: are these colleges successful because they do a great job training students, or are the students who enter their programs already so highly selected that they are destined to be successful no matter what sort of education they receive?

HOW SUCCESSFUL ARE LIBERAL ARTS COLLEGES AT EDUCATING SCIENTISTS?

Before examining the question of what it is about liberal arts colleges that makes them so successful at training future scientists, it is useful to review the objective data that indicate that they are indeed successful. Only about 8 percent of students who attend four-year colleges or universities are enrolled in baccalaureate colleges (a category that includes national liberal arts colleges).[2] Among the students who obtain Ph.D.'s in science, 17 percent received their undergraduate degree at a baccalaureate college.[3] Thus, these colleges are about twice as productive as the average institution in training eventual Ph.D.'s. On the other hand, these same schools trained only 4 percent of the eventual Ph.D.'s in engineering, so their productivity is half the average in that field. This is unsurprising, as few liberal arts colleges have engineering programs.

A more detailed view is provided by considering students trained by the top national liberal arts colleges. The institutions listed alphabetically in table 1 are representative of the best in the United States. Examination of table 1 indicates that most of the nation's top colleges educated one to three hundred of the students who obtained Ph.D.'s during the five-year period from 1991–1995. These numbers put several of the liberal arts colleges in the top hundred of all institutions in Ph.D. production (see "Rank" in table 1). However, most of the institutions ranking in the top hundred are research universities with typical enrollments of twenty to thirty thousand students, whereas the liberal arts colleges typically enroll thirteen to twenty-six hundred, roughly tenfold fewer. Thus, to compare relative Ph.D. productivity of institutions of different size, the ratio of Ph.D.'s per hundred enrolled has been calculated. Note that this ratio is approximately equal to the percentage of baccalaureate degree recipients from the college who eventually obtain a Ph.D. in science or engineering. (Because it integrates five years, it would exactly equal the percentage if one-fifth of a college's total enrollment graduated in any given year; considering attrition and the number of students who take more than four years to graduate, this is a reasonable approximation.) Thus, most of the top liberal arts colleges see between 5 percent and 18 percent of their graduates going on to obtain a Ph.D. in science or engineering (table 1, last column). Considering that their graduates majored in English, history, art, and other humanities disciplines as well as in science, this represents an astounding percentage.

Table 1. Top National Liberal Arts Colleges: How many of their baccalaureate degree students go on to receive Ph.D.'s (1991–1995)?[a]

Institution	Number of Ph.D.'s[b]	Rank[c]	Ph.D.'s/100 enrolled[d]
Amherst	118	169	7
Barnard	133	143	6
Bowdoin	89	205	6
Bryn Mawr	121	165	9
Carleton	260	69	15
Claremont McKenna	12	741	1
Colgate	132	145	5
Davidson	76	231	5
Grinnell	128	151	10
Haverford	114	174	11
Middlebury	82	219	4
Mount Holyoke	124	160	6
Oberlin	266	68	10
Pomona	135	138	10
Smith	153	120	6
Swarthmore	248	73	18
Vassar	125	158	6
Wellesley	137	137	6
Wesleyan	189	96	7
Williams	155	119	8

[a]Students who received an undergraduate degree at the listed institution and went on to receive a Ph.D. in science or engineering.
[b]Number of former graduates who received a Ph.D. from 1991–1995 (NSF 96-334).[2]
[c]Rank among all universities and colleges, based on raw numbers from previous column; the top 820 institutions were ranked.
[d](Number of Ph.D.'s) x 100/(Number of undergraduates enrolled).
Source: NSF 96-334.

For comparison, let us examine the extent to which baccalaureate degree recipients from the nation's top research universities go on to receive science and engineering Ph.D. degrees. After all, these are the institutions that grant most of the Ph.D. degrees, so one might expect their undergraduates to be oriented towards graduate education. Indeed, as shown in table 2, undergraduates from each of the nation's top research universities accounted for three hundred to more than one thousand Ph.D.'s in the recent five-year period. (The criterion of federal contract and grant money favors larger institutions and underrates those not associated with a medical school; e.g., CalTech did not make this particular list.[4] Yet the institutions on this "top twenty" list mostly remain on the list when other criteria of research success are substituted.) Most of these research universities rank among the fifty-largest producers of undergraduates who go on to obtain science and engineering Ph.D.'s (see "Rank" column). When normalized to the size of the undergraduate population, as few as 1 percent or as many as 22 percent of these undergraduates go on to obtain Ph.D.'s (see "Ph.D.'s/100 enrolled").

Table 2. Top Research Universities: How many of their baccalaureate degree students go on to receive Ph.D.'s (1991–1995)?

Institution[a]	Number of Ph.D.'s[b]	Rank[c]	Ph.D.'s/100 enrolled[d]
Columbia U.	270	65	2
Cornell U.	1090	3	9
Harvard U.	752	9	11
Johns Hopkins U.	324	50	10
M.I.T.	1000	5	22
Penn State U.	865	7	3
Stanford U.	519	23	8
U. of Colorado	500	26	3
U. of Michigan	1060	4	5
U. of Minnesota	712	10	3
U. of No. Carolina	354	43	2
U. of Pennsylvania	535	21	6
U. of So. California	192	94	1
U. of Washington	560	19	2
U. of Wisconsin, Madison	995	6	4
UC Berkeley	1590	1	7
UC San Diego	535	22	4
UCLA	781	8	3
UCSF	- 0[e]		-
Yale U.	495	27	10

[a]Alphabetical listing of institutions with the greatest federally financed research and development expenditures, 1989–1996. These twenty institutions accounted for 36 percent of the total research expenditures of the 493 institutions ranked.[4]
[b]Number of former graduates who received a Ph.D. from 1991–1995 (NSF 96-334).[2]
[c]Rank based on raw numbers from previous column; the top 820 institutions were ranked.
[d](Number of Ph.D.'s) x 100/(Number undergraduates enrolled); relative values are more precise than the actual numbers.
[e]UCSF has no undergraduate degree programs.

Source: NSF 96-334.

Table 3. Top twenty-five institutions in terms of fraction of undergraduates who go on to receive Ph.D.'s in science and engineering (1991–1995).

Institution	Ph.D.'s/100 enrolled[a]	Number of Ph.D.'s[b]
CalTech	42	368
M.I.T.	22	1000
Harvey Mudd	19	124
*Swarthmore	18	248
*Carleton	15	260
*Reed	14	182
U. of Chicago	13	435
Rice U.	12	324
Princeton U.	12	544
Harvard U.	11	752
*Haverford	11	114
Johns Hopkins U.	10	324
*Oberlin	10	266
*Pomona	10	135
*Grinnell	10	128
Yale U.	10	495
*Kalamazoo	9	115
*Bryn Mawr	9	121
Rensselaer Polytech. Inst.	9	370
Cornell U.	9	1090
Case Western Reserve U.	8	296
Stanford U.	8	519
Brown U.	8	469
*Williams	8	155
*Amherst	7	118

[a](Number of Ph.D.'s) x 100/(Number undergraduates enrolled). The Ph.D. degree is usually obtained at an institution different from the baccalaureate institution listed.
[b]Number of Ph.D.'s who obtained their baccalaureate at the listed institution (NSF 96-334).[2] Only institutions graduating more than 110 future Ph.D.'s in the five-year period are included here.
*Liberal arts colleges.

Source: tabulated by the author.

At the risk of belaboring the statistics, there is yet another useful way to compare liberal arts colleges with other institutions in terms of their training of Ph.D. scientists and engineers. All U.S. colleges and universities can be listed according to the percentage of their baccalaureate recipients who eventually receive science and engineering Ph.D.'s (table 3). With the calculation now done such that size is no longer an advantage, liberal arts colleges make an even more impressive showing.

Swarthmore, Carleton, and Reed College rank below only three very specialized science-intensive schools—CalTech, M.I.T., and Harvey Mudd—in terms of producing eventual Ph.D. scientists. This is astounding, because many of the students at these liberal arts colleges have limited interest in science, often viewing the science building as a healthy shortcut between a humanities class and an art class during the cold winter. In contrast, the top three technical schools specialize in training scientists and engineers. Perhaps it is fairer, therefore, to compare these liberal arts colleges to Chicago, Rice, Princeton, Harvard, Stanford, and Brown, which have a more similar distribution of chemistry, English, and fine arts majors. Yet the conclusion remains the same: the science students graduating from the liberal arts colleges stand up well in comparison to those graduating from the Ivy League schools and other top research universities.

The leadership of U.S. science also benefits from a disproportionate representation of liberal arts college undergraduates. Considering those elected to membership in the National Academy of Sciences in a recent two-year period who were educated in the United States, 19 percent obtained their baccalaureate degree from a liberal arts college.[5] Thus, liberal arts college graduates not only obtain Ph.D.'s but go on to excel in their field of research at a rate at least two-times greater than bachelor's degree recipients in general.

THE LIBERAL ARTS COLLEGE EXPERIENCE AND ITS INFLUENCE ON THE DEVELOPMENT OF YOUNG SCIENTISTS

In the previous section, I concluded that liberal arts colleges are remarkably successful in training eventual Ph.D.'s. They account for only a minor fraction (17 percent) of the science Ph.D. population of the nation, but when the data are normalized to the number of students these colleges enroll, it becomes clear that they are exceedingly successful on a per-student basis. The ultimate question will be one of causality: are the liberal arts college graduates successful *because of* their college experience, or independent of that experience, or perhaps even in spite of that experience? We must now, therefore, look at the experience of a liberal arts college science major—both curricular and extracurricular—and compare it to the experience of a science major at a research university. In the extreme case that the two experiences were identical, any difference in outcome would have to be ascribed to a difference in the quality of the two student populations rather than a difference in the quality of the training. Alas, as described in this section, the two environments are distinct, leaving us to grapple with the question of causality in the final section of this essay.

Formal Coursework

First, how does the science curriculum differ between liberal arts colleges and research universities? The names of the undergraduate courses and their content are similar. The differences occur in the manner in which the courses are taught. At the colleges, lecture sections rarely exceed fifty students in an introductory class and drop to perhaps a dozen in the upper-level science courses inhabited mostly by junior and senior science majors. At research universities, the numbers are typically much higher, with sometimes as many as five hundred students in a single classroom for an introductory class and as many as one hundred students in an upper-level course. In such large classes, it is difficult to avoid having students become passive recipients of information. Small classes provide the opportunity for students to engage actively in the learning process.

The teachers in the two sorts of institutions also have a very different orientation towards education. Many university professors enjoy teaching, or at least take satisfaction in their teaching, but rarely is it their first love. They were trained primarily as researchers, their promotion and tenure decisions were (or will be) based heavily on their research accomplishments, and their national and international reputations are almost totally dependent on the papers they publish and the invited research talks they present. Their peers outside their own institution will rarely know how well they teach, or perhaps even *if* they teach. In contrast, liberal arts college faculty are committed to teaching by their career choice. Their satisfaction with their own career and their reputation are heavily tied to teaching, and teaching that is simultaneously rigorous, innovative, and popular is especially prized. They are also committed to research, which at the top colleges constitutes one major criterion for promotion, but the expectations are appropriate: the research program is expected to be active and scholarly, producing publishable work and contributing to the full education of science majors (Grinnell College), in contrast to helping establish a new field, bringing in half a million dollars per year in federal funding, and resulting in several publications per year, with one in *Science* or *Nature* at least occasionally (UC Berkeley). Because of their different orientation towards teaching, the liberal arts college faculty are more accessible to students inside and outside class. The students respond by being much more interactive with faculty—willing to explore questions in depth, stopping by the office, calling faculty at home.

Given these expectations for faculty, one might expect that good or excellent teaching is *sine qua non* at liberal arts colleges, whereas it occurs almost as an afterthought at many large research universities. Such a view is overly simplistic. University science teaching also has features in which it excels. Teachers who are working at the leading edge of their field, perhaps even defining the leading edge, can bring a special type of excitement to their teaching. In some cases they share their new discoveries or those of their colleagues with their undergraduate class. They are more likely than their liberal arts college counterparts to know what material in the textbook is of current interest, and what has remained there through inertia. Thus, in some respects college teaching and research university teaching should be considered different, and not just a matter of superior versus inferior. Yet the much lower student-to-faculty ratios in the colleges are very much to their advantage, as anyone who has taught in a wide range of class sizes will attest.

The science courses taken by science majors usually have associated laboratory sessions, and here the contrast between a student's experience at a liberal arts college and a large university is even more distinct. Many liberal arts colleges integrate more open-ended, less predictable laboratory projects even in introductory courses, making them more like miniresearch experiences. While the research universities are moving in the same direction, they are severely constrained by large class sizes and low budgets, so the inquiry-based laboratories tend to be reserved for science majors in their junior and senior years. Furthermore, university lab sections are almost always supervised by TAs (teaching assistants), who are usually graduate students. While TAs are typically hard-working and enthusiastic, few of them have much teaching experience or more than a week's training, and many of them are teaching primarily because it provides their stipend. In contrast, college lab sections are typically taught by the same full-time faculty who teach the classroom sessions, which assures continuity between lecture and lab. Even more importantly, the college professor is more experienced, more committed to education, and probably more patient than a typical graduate TA.

How about courses taken outside the science building? Students choose to attend liberal arts colleges because they have broad interests, and, once there, the colleges encourage that predisposition through advising or formal requirements. As a student at Grinnell College I talked my way into Joe Wall's advanced constitutional history course, for which I lacked the prerequisites. Harold Varmus majored in English at Amherst.[6] Jennifer Doudna enjoyed medieval history and French at Pomona. Kathy Friedman was torn between majoring in English or biology at Carleton. In contrast, research universities provide students the option of focusing heavily on their favored discipline, and most science majors concentrate on the sciences. At the University of Colorado, I talk to many students who are double majors, with a typical one being biochemistry plus molecular biology. Double majors in biochemistry plus English or history are a rarity.

What impact does a liberal arts curriculum have on a career in science? In brief, the classroom and laboratory sessions are more personal, while the broad distribution of nonscience courses promotes the development of critical thinking skills and facility with written and oral communication. The influence of these features of a liberal arts education will be analyzed in a subsequent section of this essay.

Undergraduate Research

At both colleges and research universities, science majors are strongly encouraged to undertake an independent research project under the guidance of a faculty mentor. In some institutions, independent research is even a requirement for all majors. These experiences differ markedly from the laboratory sections that accompany regular courses. The problems are open-ended; typically, it is not clear how long the project will take, how accurate or even self-consistent the data will be, whether the approach and methods being used are really optimal, or whether the data will provide convincing support for or evidence against the hypothesis. In addition, the equipment and computers available for the project are typically sophisticated, up-to-date instrumentation, and expensive reagents may also be used. This is in contrast to laboratory sections, where a fixed schedule, limited budget, and constraints of having to provide a similar experience to multiple students encourage simpler, more straightforward exercises with more predictable outcomes. In short, an independent research project provides most students with their first direct experience of the life of a practicing scientist. They gain skills in identifying and solving problems, reasoning, organizing scientific data, and presenting their results and interpretations, and along with these they gain state-of-the-art technical skills. Students typically rate this experience as the most important and most memorable of their college education, and they correctly perceive it as the most relevant in terms of future employment.

> During my junior and senior school years at Pomona College, I built a high-speed photometer for astronomy research, and actually got to use it at Palomar Observatory. The profs at Pomona gave me a place in the basement to work. It was a great environment. In the basement, there was a little electronics shop with a full-time technician, and a machine shop with a full-time machinist, with both facilities there expressly for people like me.[7]

Given the importance of independent research, we next need to explore how this experience at liberal arts colleges compares to that at research universities. Two questions will be considered:

how does the quality of the research compare, and how does the value of the research experience to the student compare?

Someone unfamiliar with undergraduate research in the sciences might feel quite safe in predicting that the quality of the research would be far better at research universities than at liberal arts colleges. After all, the amount of research-grant funding, the availability of state-of-the-art instrumentation, the research reputation of the faculty, the quality of the library, and the frequency with which highly successful scientists visit to give seminars and share research ideas all weigh heavily in favor of the research universities. More specifically, while successful college professors might raise tens of thousands of dollars a year to support their research programs, successful university professors often raise half a million dollars per year. While a college would be justifiably proud to have a 400 MHz NMR (Nuclear Magnetic Resonance) spectrometer costing perhaps $400,000, research universities vie for 800 MHz NMRs that cost around $2 million. Finally, while top colleges might host an internationally known scientist to their campus for a day or two each month, top research universities are stimulated by several such seminar speakers every week, in each field of science.

Yet in spite of these obvious advantages of conducting research at a research university, there is no compelling evidence that their undergraduates end up doing better research. At both types of institutions, successful undergraduate research culminates not infrequently with a publication in a peer-reviewed journal with the student as a co-author. Such publication sets a very high standard, and certainly many good research projects do not generate publications. But publications provide a universally appreciated, objective measure of quality. With respect to the current argument, the frequency with which undergraduate research is published is not so different between colleges and universities as to mandate the conclusion that one or the other set of research projects is generally of higher quality. Furthermore, in interviews with professional scientists who are familiar with undergraduate research in both types of institutions, there was no consensus that research was generally better in one type than the other. To the contrary, most rated them to be of similar quality.

Why then do the large grants, expensive equipment, and famous laboratories available at research universities not lead to overwhelmingly superior undergraduate research opportunities? The answers are not so difficult to fathom. University research labs survive on the productivity of their graduate students, postdoctoral fellows, and technical staff. The grant money, the access to multimillion-dollar instrumentation, and typically the best projects go mainly to these more advanced scientists. Undergraduate research is promoted because of its educational value, but it does not determine the research productivity of the laboratory. In contrast, the research at liberal arts colleges is carried out almost entirely by undergraduates and faculty members, and the productivity of the undergraduates largely determines the research productivity of the laboratory. As a result, the faculty member spends more time organizing each project, more time training the students, more effort in troubleshooting the technical problems that inevitably hinder progress. At research universities, these time-consuming tasks are delegated to postdoctoral fellows or graduate students who are heavily occupied with their own research projects. The greater investment in time and effort spent with undergraduates at liberal arts colleges more or less compensates for the fact that research universities are better set up to carry out research.

In fairness, superiority of research facilities in large universities does make an impact on some undergraduates. For example, some university undergraduates participate in research in structural biology, a field dedicated to the determination of atomic-resolution pictures of biological macromolecules such as proteins. The high-field NMRs, x-ray diffraction systems, computer workstations, and synchrotron light sources required for such work can be found at many universities but are beyond the reach of liberal arts colleges, unless their students gain access by engaging in off-campus research. As another example, undergraduates at research universities occasionally participate in a “hot” project that becomes internationally acclaimed and is published in *Science* or *Nature* because of its impact and broad interest. Such an outcome is very rare for undergraduate research at a small college. Yet the fraction of undergraduate research projects that are so exceedingly successful is small even at research universities. The general situation is that there is a wide range in the quality of undergraduate research at both colleges and research universities, and that the two distributions overlap extensively.

We now move from the quality of the research itself to the quality of the research experience—how well does it promote the development of the scientist-in-training? The special feature of undergraduate research at colleges is that it is much more personal. The college professor guides the research of a small number of students at a time, and therefore spends much more time with them than a typical university professor. The quality of mentoring of undergraduates can be very high when it is direct, faculty to student, rather than mediated through a postdoctoral fellow or graduate student.

> [My] physics research was not as intense or cutting-edge as at a university, but I think I had much more attention from my advisor than I would have at a university. For instance, I remember calling him at home one evening to tell him of an important paper I had found; he walked back to campus to talk with me about it that night.[8]

Other liberal arts graduates speak of the high level of responsibility and independence engendered by their undergraduate research experience. In the absence of roomfuls of graduate students or postdocs with expertise in every imaginable technique or procedure, the student needs to be self-reliant and innovative. Furthermore, a senior undergraduate may be called upon to help mentor and train the new undergraduate entering the lab. In a university lab, that same senior undergraduate would be near the bottom of the hierarchy in terms of level of experience.

In summary, the personal attention given by the professor often leads to an intense and highly focused research experience in a liberal arts college. Those who have had such an experience prize it greatly and consider it to have been highly influential in their development as scientists.

WHY ARE LIBERAL ARTS COLLEGE SCIENCE STUDENTS SO SUCCESSFUL?

A Nurturing Environment

Many of the features of a liberal arts education already mentioned above combine to create a very comfortable and supportive environment for learning. These features include the low student-faculty ratio and the involvement of faculty in the whole education of the students—laboratory sections as well as classes. The faculty are much more available for casual interactions with undergraduates than are university professors, whose time is fragmented by expectations that they contribute to the diverse missions of a university: undergraduate education, graduate education, creation of new knowledge, developing a national and international presence, protection of the university's intellectual property through patents, public service, and perhaps even aiding the economic development of their state.

> There were only two of us in the lab, so we received a great deal of personal attention from our professor. She was always there for us. We have great students here at Yale, too, but they are handed off to a graduate student or postdoc for their research. It doesn't compare with the quality of the research experience I had at Pomona.[9]

There may also be students at universities who see their professors as such giants that they cannot imagine themselves attaining such heights. The more approachable faculty at liberal arts colleges provide less intimidating role models. The students are encouraged to maintain their interest in science during the critical period when their maturity—both intellectual and personal—is growing to the point where they can envision themselves obtaining a Ph.D. Speaking more generally, at a liberal arts college the undergraduates are the center of attention, the reason for the existence of the institution. This can engender confidence and a feeling of self-worth.

Cross-training in the Humanities and Arts

Athletes often incorporate a variety of exercises not directly related to their sport to improve their overall strength and conditioning. For example, swimmers and soccer players cross-train by lifting weights. The cross-training may exercise key muscle groups more effectively than spending the same amount of time working out in the sport of interest. Analogously, a liberal arts education encourages scientists to improve their "competitive edge" by cross-training in the humanities or arts. Such academic cross-training develops a student's ability to collect and organize facts and opinions, to analyze them and weigh their value, and to articulate an argument, and it may develop these skills more effectively than writing yet another lab report.

What is the value of such intellectual cross-training? Just as mathematics is considered to be good exercise for the brain even for those who will never use calculus in the future, so the study of great books, history, languages, music, and many other nonscience fields is likely to hone a scientist's ability to perceive and interpret the natural world. More specifically, in history, literature, and the arts one is presented with diverse, often mutually contradictory "data"—different points of view due to incomplete knowledge or the different backgrounds of those doing the viewing. One learns to distill the critical elements from the irrelevant, synthesize seemingly discordant observations, and develop a strong argument. While scientific data are commonly thought to exist on a different plane—absolute, precise, unambiguous, and above reproach—such is rarely the case. Random error and systematic deviations must be taken into account. Choices of experimental design inevitably affect the results obtained. Interpretations are often heavily influenced by expectations, which in turn are heavily influenced by earlier conclusions published in the research literature. Scientists need the same skills as humanists to cut through misleading observations and arrive at a defensible interpretation, and intellectual cross-training in the humanities exercises the relevant portions of the brain.

Another obvious value of humanities classes for a scientist is the development of communication skills. Success in science, like many other endeavors, is highly dependent on the scientist's ability to write manuscripts and research-grant applications that are well organized, clear, and persuasive. Oral communication skills are equally important, including the ability to present one's research in a manner that is not only convincing but also exciting and perhaps even entertaining. The most brilliant research accomplishments make no impact unless they can be communicated to an external audience.

> My present ability, such as it is, to distill the results of structural analysis into paragraphs of text I attribute directly to the hours spent in the analysis of English verse. A strong emphasis on performance on the stage and in oral interpretation of text has also helped with science lectures.[10]

Writing papers for humanities classes allows students to develop skills in stating their position, evaluating it critically, presenting evidence (internal, such as quotations from the work being analyzed, and also external, from other authors), and organizing their argument. Sketching, painting, and sculpting help a student to develop skills in perception and in the construction of visual aids that illustrate scientific observations or models. Like cross-training in sports, exercising one's communication skills in areas unrelated to science may be more advantageous than taking yet one more science course.

The value of the broadening experience of a liberal arts education is unlikely to be quantifiable, and verifying its impact is therefore problematic. Nevertheless, many of us who have enjoyed such an education are convinced that it has benefited us as scientists. This practical benefit is in addition to the stated goal of a liberal arts college education: to enhance one's whole life.

Counterpoint: Some Disadvantages of a Liberal Arts College Education

Two educational features in which liberal arts colleges cannot match research universities have already been mentioned: some undergraduates at research universities have access to equipment and reagents that enable more sophisticated research projects than are possible even at well-equipped colleges, and the special thrill of being present when important discoveries are being made is much more likely to be encountered at a research university. Neither of these experiences is common, so the number of university undergraduates who derive these benefits is limited.

Two other areas in which liberal arts colleges may fall short of research universities deserve discussion. First, it was noted by one liberal arts college graduate that there may be a real danger of setting one's goals too low. If world-class discovery research is not being carried out in the same building, it may make it more difficult for talented students to appreciate what such research involves and to picture themselves engaged in it. Yet this may be more of a concern for liberal arts colleges that draw many of their students from local communities; the top national colleges such as those listed in table 1 are very successful in placing their students in the most competitive graduate programs. A second possible shortcoming of colleges was mentioned by many of those interviewed: the colleges are very sheltered, and their students generally have no concept of the "real" research world of million-dollar research grants, press releases, and cutthroat competition. The counterargument is that premature exposure to these practical issues could actually discourage many students from pursuing a career in science. In any case, it may be inconsistent to extol the virtues of the friendly, supportive, nurturing environment found at colleges and simultaneously bemoan their isolation from the politics of big science.

Cause or Effect?

The top liberal arts colleges are highly selective in their admissions, and they turn out very successful scientists. Are they successful because they do a great job, or because the input is of such high quality? We do not have the luxury of being able to take two identical groups of students, place one group in liberal arts colleges and the other in research universities, and return four or more years later to evaluate their relative success. However, it is noteworthy that the most selective private research universities (Harvard, Princeton, Stanford, Columbia, and Yale) are more selective than any of the liberal arts colleges, and their students taken as a group have higher SAT test scores than the entering classes of any of the liberal arts colleges. Yet their efficiency of production of Ph.D.'s, while excellent, lags behind that of the top liberal arts colleges (table 3). Clearly the liberal arts institutions are doing much more than simply recruiting talented students and hoping for their eventual success. On a more subjective note, in interviews with successful liberal arts college science graduates, none of them chose to attribute the success of the colleges primarily to their high selectivity. Instead, they commented that the quality of the incoming students and the quality of the education must both contribute.

Further confounding this question of nature versus nurture is the tendency for talented students to be encouraged to achieve ever more when surrounded by other high achievers. There has recently been renewed discussion of the influence of peers relative to parents in determining a child's values, aspirations, and ultimate success.[11] Perhaps there is also a tendency to underestimate the effect of the peer group on the quality of education. In this regard, the colleges may be successful because they surround a student not simply with other bright students who performed well on standardized tests but with students who are excited about learning, who are confident but not overconfident about their own abilities, and who enjoy working hard.

Thus we arrive at the conclusion, perhaps obvious from the outset, that innate talent and a quality education both contribute to the success of science students graduating from liberal arts colleges. Intelligence, creativity, and hard work can take a student far, but they constitute an even more powerful combination when channeled, guided, and motivated by excellent teachers in an environment supportive for learning.

SUMMARY AND OUTLOOK

Liberal arts colleges as a group produce about twice as many eventual science Ph.D.'s per graduate as do baccalaureate institutions in general, and the top colleges vie with the nation's very best research universities in their efficiency of production of eventual science Ph.D.'s. On a more subjective note, when highly successful scientists compare their liberal arts college education to what they likely would have received at a large research university, most rate their college experience as a substantial advantage to their career. Distinguishing characteristics of liberal arts college science education include small classes, a faculty that is available to the students and focused largely on undergraduate education, and the incorporation of courses in the humanities and arts that promote intellectual "cross-training." Independent research at liberal arts colleges does not approach the leading edge of scientific fields as often as that carried out at research universities, but it benefits from highly personal one-on-one interactions between students and faculty mentors, making for an overall experience that often surpasses that at large universities. Reinforced by these features, the liberal arts college science education is highly valued by its graduates and contributes to the nation's strength in science at a level disproportionate to its size.

Will science education at the liberal arts colleges continue to thrive in the next century? After all, scientific supplies are increasing in cost more quickly than the general rate of inflation. Instrumentation of an ever-increasing variety and technological sophistication is essential for scientific research, and it can be argued that at least some of it must be made available to students lest their training become dated. However, the national liberal arts colleges have been very successful in garnering internal resources, federal and private foundation grants, and donations to obtain supplies and equipment that are more up-to-date than those available in undergraduate laboratories at many major universities; given their demonstrated success in using these resources to enhance the education of successful students, the colleges have built a firm foundation for continuing to obtain the scientific resources they desire. Furthermore, if funds for supplies and equipment tighten, imaginative faculty will find ways to substitute less expensive laboratory exercises that have similar pedagogical value. What the colleges cannot change without compromising their very heart and soul is their personalized approach to education and their committed faculty, which add up to a very expensive approach to higher education. The challenge to continue to make such an education available to students with diverse economic backgrounds cuts across disciplines, and is not specific to the sciences. This is the challenge of the liberal arts college in the twenty-first century.

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ENDNOTES

[1]David Davis-Van Atta, Sam C. Carrier, and Frank Frankfort, *Educating America's Scientists: The Role of the Research Colleges* (Oberlin, Ohio: Oberlin College, 1985); Sam C. Carrier and David Davis-Van Atta, *Maintaining America's Scientific Productivity: The Necessity of the Liberal Arts Colleges* (Oberlin, Ohio: Oberlin College, 1987); Sophie Wilkinson, "Liberal Arts Colleges are Good Ph.D. Incubators," *Chemical & Engineering News* (3 August 1998): 45–46.

[2]The remainder attend research universities (the 125 leaders in federal funding), doctoral universities (e.g., Iowa State University, University of South Florida, Howard University, and Rensselaer Polytechnic Institute), master's colleges and universities (e.g., Glassboro State College, Old Dominion University, and Creighton University), or specialized institutions that focus primarily on technical or professional programs (e.g., New Jersey Institute of Technology, Princeton Theological Seminary, and Teacher's College of Columbia). These categories are taken from the 1994 Carnegie Classification as described in NSF 96-334 [National Science Foundation, *Undergraduate Origins of Recent (1991–1995) Science and Engineering Doctorate Recipients, Detailed Statistical Tables,* NSF 96-334 (Arlington, Va.: NSF, 1996)].

[3]These data concern 1991–1995, the most recent five-year period for which data have been compiled (NSF 96-334, p. 6); data for the previous five-year period are similar.

[4]National Science Foundation, Division of Science Resources Studies, *Academic Research and Development Expenditures: Fiscal Year 1996*, NSF 98-304, ed. M. Marge Machen (Arlington, Va.: NSF, 1998).

[5]Data for 114 members elected in 1997 and 1998, compiled by Judith Harrington, Membership Director, National Academy of Sciences.

[6]Scientists interviewed were David Baltimore (B.A. in Chemistry, 1960, Swarthmore), President, Cal Tech, Nobel Prize in Medicine (1975); David P. Corey (B.A. in Physics, 1974, Amherst), Professor, Harvard Medical School; Jennifer A. Doudna (B.A. in Chemistry, 1985, Pomona), Assistant Professor, Yale, Markey Scholar, Searle Scholar, Packard Fellow; Katherine L. Friedman

(B.A. in Biology, 1990, Carleton), Postdoctoral Fellow, HHMI Predoctoral Fellow at the University of Washington; Richard H. Gomer (B.A. in Physics, 1977, Pomona), Associate Professor, Rice University; John Kuriyan (B.S. in Chemistry, 1981, Juniata), Haggerty Professor, Rockefeller University; Joan A. Steitz (B.S. in Chemistry, 1963, Antioch), Henry Ford II Professor, Yale; and Harold E. Varmus (B.A. in English, 1961, Amherst), Director, National Institutes of Health, Nobel Prize in Medicine (1989). In addition to their academic appointments, Corey, Doudna, Gomer, Kuriyan, and Steitz are Investigators of the Howard Hughes Medical Institute.

[7]Gomer, interview.

[8]Corey, interview.

[9]Doudna, interview.

[10]Kuriyan, interview.

[11]M. Gladwell, "Do Parents Matter?" *The New Yorker* (17 August 1998): 54–64, discusses the work of J. R. Harris, *The Nurture Assumption: Why Children Turn Out the Way They Do* (New York: Free Press, 1998).