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MEASURING SCIENCE: AN
EXPLORATION

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ABSTRACT

This paper examines the available U.S. data on academic R&D expenditures and the number of papers published and the number of citations to these papers as possible measures of "output" of this enterprise. We look at these numbers for science and engineering as a whole, for 5 selected major fields, and at the individual university-field level. The published data in *Science and Engineering Indicators* imply sharply diminishing returns to academic R&D using published papers as a "output" measure. These data are quite problematic. Using a newer set of data on papers and citations, based on an "expanding" set of journals and the newly released BEA R&D deflators, changes the picture drastically, eliminating the appearance of diminishing returns but raising the question of why the input prices of academic R&D are rising so much faster than either the GDP deflator or the implicit R&D deflator in industry. A production function analysis of such data at the individual field-university level follows. It indicates significant diminishing returns to "own" R&D, with the R&D coefficients hovering around 0.5 for estimates with paper numbers as the dependent variable and around 0.6 if total citations are used as the dependent variable. When we substitute scientists and engineers in place of R&D as the right hand side variables, the coefficient on papers rises from 0.5 to 0.8, and the coefficient on citations rises from 0.6 to 0.9, indicating systematic measurement problems with R&D as the sole input into the production of scientific output. But allowing for individual university-field effects drives these numbers down significantly below unity. Since in the aggregate both paper numbers and citations are growing as fast or faster than R&D, this finding can interpreted as leaving a major, yet unmeasured role, for the contribution of spillovers from other fields, other universities, and other countries.

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MEASURING SCIENCE: *AN EXPLORATION*

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Introduction

While the definition of science and of its borders is ambiguous, it is clearly a major sector of our economy and the source of much of past and future economic growth. In this paper we look primarily at "academic" research (as defined by the NSF) and its locus, the research universities. It is a major sector of the total U.S. "research" enterprise, accounting (in terms of performance) for only 13 percent of the total R&D dollars spent in the US in 1993 but 51 percent of all basic research expenditures and 36 percent of *all* doctoral scientists and engineers primarily employed in R&D (1). Other major R&D performing sectors, such as industry, have been studied rather extensively in recent years, but quantitative studies of science by economists are relatively few and far between. (See Adams for an earlier attempt and Stephan for a recent survey and additional citations (2-3)).

The limited question which we would like to address in this exploratory paper is posed by the numbers that appear in the latest issue of *Science and Engineering Indicators (1993)*: during 1981-91 total R&D performed in the U.S. academic sector grew at 5.5 percent per year in "real" terms while the total number of scientific articles attributable to this sector grew by only 1.0 percent per year (1). Is this discrepancy in growth rates an indication of sharply diminishing returns to investments in science? Or is there something wrong with the basic data or with our interpretation of them? (For a discussion of similar

issues in the analysis of industrial R&D data see Griliches (4)) These official measures of "activity" in U.S. science are plotted in Figure 1 on a logarithmic scale. We shall try to examine this puzzle by using detailed recent (1981-1993) data on R&D expenditures, papers published, and citations to these papers, by major fields of science, for 50+ of the major research universities. But before we turn to these calculations a more general discussion of the measurement issues involved may be in order.

The two major outputs of academic science are new ideas and new scientists. The latter is relatively easy to count and its private value can be computed by capitalizing the lifetime income differentials that result from such training (5). Ideas are much more elusive (6). As far as direct (internal) measures of scientific output are concerned, the best that can be done at the moment is to count papers and patents and adjust them for the wide dispersion in their quality by using measures of citation frequency. That is what we will be doing below. (For an analysis of university patenting see Henderson et al. (7). For an analysis of citations in industrial patents to the scientific literature see Narin*, and Katz et al. (8).)

Indirect measures of the impact of science on industrial invention and productivity are based either on survey data (9-11) asking firms about the importance of academic science to their success, case studies of individual

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*Narin, F. (1995) "Linking Biomedical Research to Outcomes--The Role of Bibliometrics and Patent Analysis," presented at the NIH Economics Round-table on Biomedical Research, Bethesda, MD, Oct. 18-19, 1995. Unpublished paper (Computer Horizons Inc., Haddon Heights, New Jersey).

inventions (12-15), or various regression analyses where a measure of field or regional productivity (primarily in agriculture), is taken to be a function of past public R&D expenditures or the number of relevant scientific papers (2, 16-18). All these studies are subject to a variety of methodological-econometric problems, some of which are discussed in Griliches (19-20). Moreover, none of them can capture the full externalities of science and thus provide only lower-bound estimates for its contributions.

Direct measures of scientific output such as papers and the associated citation measures have generated a whole research field of bibliometrics in which economists have been only minor participants. (See Van Raan (21) and Elkana (22) for surveys and additional references). Most of this work has focused on the measurement of the contribution of individual scientists or departments within specific fields (see Stigler (23) and Stephan (3) in economics and Cole and Cole (24) in science more generally). Very few have ventured to use it as a measure of output for a field as a whole (Price and Adams (25-26) at the world level and Pardey (27) for agricultural research, are some of the exceptions). The latter is bedeviled by changing patterns of scientific production and field boundaries and the substantive problems of interpretation implied by the growing size of scientific literature, some of which we'll discuss below.

The Aggregate Story

Returning to the aggregate story depicted in Figure 1 we note that the number of scientific papers originating in U.S. universities given in the S&EI grew significantly slower during 1981-91 than the associated R&D numbers. But reading the footnote in SE&I raises a clear warning signal. The paper numbers

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given in this source are for a *constant* set of journals! If science expands but the number of journals is kept constant, the total number of papers cannot really change much (unless they get shorter). U.S. academic papers could also expand in numbers if they "crowded out" other paper sources such as industry and foreign research establishments. But in fact, the quality and quantity of foreign science was rising over time, leading to another source of downward pressure on the visible tip of the science output iceberg, the number of published papers. If this is true, than the average published paper has gotten better, or at least more expensive, in the sense that the resources required to achieve a certain threshold of results must have been rising in the face of the increase in competition for scarce journal space. Another response has been to expand the set of relevant journals, a process that has been happening in most fields of science but is not directly reflected in the published numbers. (The published numbers do have the virtue of keeping a dimension of the average paper quality constant, by holding constant the base period set of journals. This issue of the unknown and changing quality of papers will continue to haunt us throughout this exercise.)

We have been fortunate in being able to acquire a new set of data (INST100) assembled by ISI (Institute of Scientific Information), the producers of the Science Citations Index, based on a more or less "complete" and *growing* number of journals, though the number of *indexed* journals did not grow as fast as one might think (see Figure 2). The INST100 data set gives the number of papers published by researchers from the 110 major U.S. research universities, by major field of science and by university, for the years 1981-93. (See Appendix A for a somewhat more detailed description of these and related data). It also gives total citation numbers to these papers for the period as a whole and for a moving 5-year

window (i.e., total citations during 1981-5 to all papers published during this same period). This is not exactly the measure we would want, especially since there may have been inflation in their numbers over time due to improvements in the technology of citing and expansion in the numbers of those doing the citing, but it is the best we have.

There are also a number of other problems with these data. In particular, papers are double counted if authors are in different universities and the number of journals is *not* kept constant, raising questions about the changing quality of citations as measures of paper quality. The first problem we can adjust for at the aggregate and field level (but not university); the second will be discussed further below. Table 2 shows that when we use the new, "expanding journals set" numbers, they grow at about 2.2 percent per year faster, in the aggregate. Hence, if one accepts these numbers as relevant, they dispose of about half of the puzzle.

Another major unknown is the price index that should be used in deflating academic R&D expenditures. NSF has used the GDP implicit deflator in the S&EI and its other publications. Recently, the Bureau of Economic Analysis (BEA) produced a new set of "satellite accounts" for R&D (28), and a new implicit deflator (actually deflators) for academic R&D (separately for private and state and local universities).[†] This deflator rises significantly faster than the implicit GDP deflator during 1981-91, 6.6 percent per year versus 4.1 for the latter. It rises even faster relative to the BEA implicit deflator for R&D performed in industry, which is only growing at 3.6 percent per year during this period. It implies that doing R&D in universities rather than in industry became more expensive at the rate of 3 percent per year! This is a very large discrepancy, presumably produced

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[†]See also NIH (29) and Jankowski (30).

by rising fringe benefits and overhead rates, but it is not fully believable, especially since one's impression is that there has been only modest growth in real compensation per researcher in the academy during the last two decades. But that is what the published numbers say! They imply that if we switch to counting papers in the "expanding set" of journals and allow for the rising relative cost of doing R&D in universities, there is no puzzle left. The two series grow roughly in parallel. But it does leave one with the question, to be pursued further on another occasion, why are the cost of doing academic R&D rising this fast? Is that a different manifestation of diminishing returns (rising costs) to it?

Figure 3 adds these new measures to Figure 1 and shows that the concern about diminishing returns at the aggregate level was an artifact of the "fixed journals" aspect of the official data and the use of the implicit GDP deflator to deflate academic R&D. In the aggregate, the new measure of the total number of papers still grows more slowly than the NSF-deflator-based "real" R&D expenditures but is now close to the growth rate of the BEA-deflator-based R&D numbers. On the other hand, total citations, which one is tempted to interpret as "quality" weighted paper numbers, grow at about the same rate as appropriately lagged and weighted NSF-based R&D numbers and significantly faster than the similar BEA-based numbers. (The citations numbers were adjusted for the growing double-counting of multi-authored papers across universities.)

Of course, these new numbers must also be interpreted with care. There are both factual and conceptual questions that need further investigation. To what extent does the time profile in the growth of papers and citations in the INST100 data set represent actual growth in the size of the relevant scientific literatures or does it just reflect the "coverage" expansion by ISI of an already existing body of

literature? A more difficult question, given the public good nature of scientific papers, is raised by the growing number of citations that come from an expansion in the size of the interconnecting literatures and also from changes in citation practices. If Russians are suddenly allowed to read Western science and publish in Western journals, and if their journals are now indexed by ISI, should that be counted as an increase in the output of U.S. science? Is science in 1990 better than in 1980 just because it *reaches* more scientists today? Yes, in its public good effect. Not necessarily so, if we want a pure production concept. But before we continue this discussion we shall first turn to consider some of these issues at the more "micro" field-by-university level.

Fields

Table 1 shows the levels of our major variables in 1989, for five different fields of science: biology, chemistry, mathematics, medicine, and physics (we have excluded the more amorphous field of engineering and technology , the social sciences, and several other smaller fields, such as astronomy). The first two columns are based on data from *Science and Engineering Indicators,* for all U.S. academic institutions (1). The second half of this Table is based on a new unpublished data set from ISI (Institute for Scientific Information) and refers to the top 110 research universities. (See the Data Appendix for more detail.) The five fields that we shall examine accounted for about 54 percent of total academic R&D in 1989 and 74 percent of all scientific papers (in the INST100 data set). Within these fields biology and medicine clearly dominate, accounting for 80 percent of total R&D in this subset of fields and 50 percent of all papers.

Table 2 gives similar detail by major field of science. If one uses the NSF-SE&I based R&D and paper numbers, all of the examined fields have done badly. Switching to the INST100 population, BEA implicit indexes deflated R&D, and the unduplicated number of papers in the ISI "expanding journals" set, biology, chemistry, and physics are now doing fine, but medicine and especially mathematics still seem to be subject to diminishing returns. The numbers look better if one uses total citations as one's "output" measure, but after adjusting them for growing duplication (we can make this adjustment only at the total field level) the story of mathematics is still a puzzle, and adding computer sciences to it does not solve it.[‡]

Fields-by-Universities

To try and get a better understanding of what is happening to research productivity we turn to the less aggregated and more relevant level of fields in individual universities. We say more relevant because with more disaggregated data we are likely to match better research outputs with research inputs. In principle, data on the individual research project would improve the match, but these data are not available.

We have reasonable data on approximately 50 universities, 5 science fields, and 21 years (see the Appendix). In reality we have two distinct time series on numbers of scientific papers attributed to a particular university, one from Computer Horizons (CHI) covering 1973-1984, the other from ISI covering 1981-1993. In addition we have citation data from ISI for the second period only,

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[‡]The parallel numbers (in Table 2) for mathematics and computer sciences combined are: 7.8, 5.6, n.a., 1.7, 1.4, 1.2, (0.9).

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which appear in the form of five-year moving sums or "windows", and are thus overlapping from year to year. Therefore, for the analysis of citations we use just three, effectively non-overlapping windows ending in 1985, 1989, and 1993, but appropriately recentered on 1982, 1986, and 1990 because of the timing of citations, which are concentrated on the earlier years of any window.

Table 3 shows that the universities in our sample accounted for about two-thirds of the R&D, papers, and citations in the full INST100 data from ISI covering the top 110 research universities in the year 1989.

We estimate several versions of a "production function", of the form

$$y = \alpha + \beta W(r) + \gamma X + \lambda t + u$$

where y is the logarithm of one of our measures of output (papers or citations), $W(r)$ is the logarithm of a distributed lag function of past R&D expenditures, or the number of scientists and engineers, or both, X is a set of other "control" variables such as type of school, and t is a time trend or a set of year or period dummy variables, while u represents all other unaccounted forces determining this particular measure of output. Our primary interest centers on the parameters β and λ. The first would measure the returns to the scale of the individual (or rather, university) research effort level, if everything else were correctly specified in this equation, while the second, will indicate the changing general level of "technology" used to convert research dollars into papers or citations.

Table 4 summarizes our estimates of this relationship. The first two columns report the estimated coefficients of the logarithm of lagged R&D with weights .25, .5, and .25 respectively for R&D lagged one, two, and three years, and the coefficients of a linear time trend, based on two different paper series and

different time periods. The estimated R&D coefficients hover around .5, indicating rather sharply diminishing returns to the individual university effort, with medicine having a somewhat higher coefficient and mathematics an even lower one.[§] Again, except for mathematics, the trend coefficients are positive and significant, indicating that this tendency to diminishing returns at the individual university level is counteracted to a significant extent by the external contribution of the advances in knowledge in the field (and in science) as a whole, arising both from the R&D efforts in other universities, other institutions (such as the NIH), and other countries. Other variables included in the list of X's, such as indicators whether a university was listed among the top 10 research universities, whether it was private, and the size of its doctoral program, were significant and contributed positively to research "productivity" but did not change the estimated β and λ coefficients significantly.

Columns 3 and 4 of Table 4 use five-year sums of papers and citations centered on 1982, 1986, and 1990 as their dependent variables. They pool the three non-overlapping cross-sections, allowing for different year constants and including the above mentioned "type of school" control variables. For the citations regressions we redefine our R&D variable to reflect the fact that the dependent variable includes citations to 5 years worth of papers, but in different proportions. We assume, and that is consistent with the available evidence, that each of the 5-year "windows" of citations refers only to 4 years of lagged papers

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[§]This is still true if computer sciences are included in the definition of "mathematics."

in 1, 2, 3, and 4 proportions.[¶] Combined with our assumed three year lag of papers behind R&D, this gives a relatively long lag structure for the 5-year citations relevant distributed lag of R&D (CWRD: .025, .100, .200, .300, .275, .100).

The results of using five year sums of papers (col. 3) are essentially the same as those using annual numbers (cols. 1 and 2). The estimated R&D coefficients in the citations regressions (col. 4) are significantly higher, however, in all fields, by about 0.1+. Since these are basically cross-sectional results, they are not an artifact of the expanding journal universe, and indicate that additional R&D investments produce not only more papers but also higher quality papers (at least as measured by the average number of citations that they receive). When we run regressions of citation numbers on both paper numbers and R&D, both variables are "significant", with the papers coefficient at about 1.1, indicating some increasing returns in terms of citations to the size of the research output unit (perhaps a larger opportunity for self-citation?), and a consistently significant R&D coefficient of about 0.1+. Still, the "total" R&D coefficients in column 4 are far below unity.

Formal R&D expenditures may not measure correctly the total research resource input, especially in smaller institutions. The only other resource measure available to us is total scientists and engineers (within the field and university). Table 5 looks at the effect of varying the measure of science input on the estimated elasticities of science output. We compare the distributed lag function of real R&D of Table 4 with a similar distributed lag function of scientists and engineers (S&Es), and for good measure we report a third specification that

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[¶]This is about right. The number of current (i.e., lag zero) citations is only 1 to 1.5 percent of the total.

includes both scientists and engineers and real R&D per scientist and engineer[*].
The output measures are 5 year windows of papers and citations. However, data
on scientists and engineers by field and university were not collected after 1985 so
that we can use only two cross sections of papers and citations centered on 1982
and 1986, not the three reported in Table 4. All variables are in logarithms.

The results of this switch are interesting. The elasticities reported in Table
5 are all highly significant by conventional standards, but the elasticities
calculated using S&Es are on average 0.26 higher: the paper elasticity clusters
around 0.8 rather than 0.5, while the citation elasticity is 0.9 on average rather
than 0.6. When we add R&D per S&E as a separate variable the main effect of
scientists and engineers is about the same but there is an additional effect,
generally somewhat smaller yet still significant, of per capita R&D. These
findings suggest that not all research is financed by grants, but that departments
with more generous support per researcher are more productive. More of the
research in the smaller programs is being supported by teaching funds, because
the S&E input measure is larger in these programs relative to real R&D. This
interpretation is borne out by the comparison between biology, medicine, and
chemistry, where a larger fraction of researchers earn grants, with mathematics
and physics, where grants are less common. The jump in the elasticity when
S&Es are substituted for R&D is only 0.1 for chemistry, biology, and medicine
but it is 0.5 for mathematics and physics. Of course, in all the fields we are
counting total S&Es, not research S&Es. Less of these are researchers in the
smaller programs, so that to some extent the human resources used in research are
being overstated, more so in the smaller programs than in the larger ones.

The last column of Table 4 reports parallel results using an 8-year *difference* in these moving average variables, allowing thereby for the possible influence of unmeasured individual university effects on research productivity. (The same is also true for the 4-year *difference*-based results, not shown, using the S&E variables reported in Table 5.) The estimated R&D coefficients are now much smaller though still "significant", except for medicine, where they effectively vanish, indicating that there is a large university effect that dominates this result and that there is little information in the *changes* in R&D or S&E numbers during this period.

There may also be problems arising from the differential truncation caused by the 5-year window in the ISI data. If larger R&D programs are directed to more basic questions, they could be producing a smaller number of more and *longer* cited papers. Thus, cutting off the citation count at 5 years would differentially underestimate their contribution. That something like that may be happening can be seen in Table 6 where we report parallel results for a cross-section based on 13 years of citations (in 1981) and compare it to another single-year cross section of papers (in 1989) with only 5 years worth of citations. The longer window does yield higher coefficients, but only in the life-sciences (biology and medicine) is the difference substantively significant. Moreover, there is no indication that if the window were lengthened even further, the estimated coefficients would approach unity. In parallel intermediate different window-length regressions (not shown here), the estimated coefficients peak around the 9 to 11 year window and do not rise significantly thereafter.

Looking at the estimated year constants in the lower half of Table 4 we see that they are all substantial in size and statistically "significant" by 1993, except

for mathematics. Allowing for the growth in multi-university papers (based on the numbers in Table 2), would reduce these numbers somewhat, but not substantially (to .37 for biology, .19 chemistry, .36 medicine, and .33 in physics in the 1993 citations column). Dividing these numbers by 8 (the difference in years between 1993 and 1985) would give another estimate of the contribution of "external" science, per year, to research productivity.

An alternative interpretation for an estimated $\beta < 1$ would focus on the possibility of errors in allocating both R&D expenditures and papers within universities to particular fields. If papers in universities are created both by research expenditures in the designated fields and by research expenditures in other relevant or miss-classified fields within the university, then an aggregate regression, aggregating over all fields of interest may yield higher R&D coefficients. That's what may be implied by the last row in Table 6, where the coefficients based on aggregated data are significantly higher and now approach unity. Note that this measures either errors or *within university across fields of science spillovers*. It does not reflect possible contributions of new knowledge eminating from other universities and countries. (This finding requires additional analysis to check its robustness against other unmeasured university effects and different field aggregations.)

It is especially difficult to separate biology from medicine. In the final line of Table 5 we collapse biology and medicine into a biomedical composite. The results suggest that there is indeed some difficulty in distinguishing R&D in biology from R&D in medicine, since the composite R&D elasticity is higher than the R&D elasticities computed separately for biology and medicine. The results

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of the aggregation for the S&E measure are more mixed and appear to be an average of the separate estimates.

There are many loose ends in the analysis as of now. As indicated above, we have only started exploring the data available to us and the range of possible topics it could throw some light on. In the intermediate run we could do more with the panel structure of the data and with other indication of university quality. We could also explore directly within university spillovers from neighboring fields of science and the role of Ph.D. training in the research productivity nexus. In the longer run and with more resources, better data could be assembled, allowing us to analyze citations to single year papers and to more finely defined fields. All of this, however, will still leave us looking "within" science, at its internal output, without being able to say much about its overall, external societal impact.

An Inconclusive Conclusion

From the numbers we have one could conclude that U.S. academic science has been facing diminishing returns in terms of papers produced per R&D dollar, both because the rising cost of achieving new results within specific scientific fields and because of rising competition due to the expanding overall size of the scientific enterprise, both within the United States and worldwide, impinging on a relatively slowly growing publication outlets universe. In terms of total citations achieved per R&D dollar, the picture is somewhat brighter, indicating a rising quality of U.S. science in the face of such difficulties, though this interpretation is clouded by the question whether the actual science is better or is it just being

evaluated on a larger and changing stage (the growing number of journals and papers in the world as a whole and changing citation practices).

Even though the within-science costs of new knowledge may be rising, its social value may also be rising as our economy grows and also as it continues to contribute to a growing worldwide economy. But to measure this will require different data and different modes of analysis. Just trying to connect it to the growth of GNP will not do, since most of the output of science goes into sectors where its contribution is currently not counted.** Measuring the true societal gains from medical advances or from the vast improvements in information technology is in principle possible but far from implementable with the current state of economic and other data. That is a most important task that we should all turn to. But right now, unfortunately (or is it fortunately?), we have to leave it for another day.

Data Appendix

The data at the field and university level used in this paper derive from National Science Foundation Surveys and two bibliometric sources. We took total R&D expenditures from the CASPAR data base of universities created for the National Science Foundation (Quantum Research Corporation, 1994). The underlying source for university R&D is NSF's annual Survey of Scientific Expenditures at Universities and Colleges, which collects R&D by science and engineering discipline, source of funds, and functional category of expenditures. R&D is available for the entire period 1973-1992 with the exception of a few disciplines. Our R&D deflators are the BEA's newly available sectoral R&D

**See Griliches (4, 31) for additional discussion of these issues.

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price indexes, which convert current dollar R&D expenditures into constant 1987 dollars separately for private and public universities.

The data on papers and citations come from two distinct sources. The earlier data were produced for NSF by Computer Horizons Incorporated (hereafter, CHI) and cover the period 1973-1984, based on the original Institute for Scientific Information (hereafter, ISI) tapes. These earlier data report numbers of papers by university and field published in an expanding set of the most influential journals in science, rising in number from about 2100 journals in 1973 to about 3300 in 1984. The later data were constructed by the ISI itself for the 1981-1993 period. Thus we have an overlapping period in the two data sets for comparative purposes. The journal selection criteria are slightly different in the ISI data than for CHI and the the number of journals is somewhat larger. At the present time the ISI journal set includes roughly 4000 journals in the sciences and 1500 journals in the social sciences. A second difference from the CHI data is that ISI counts multiple authored papers in different universities as whole papers up to 15 times, whereas CHI assigns equal shares of the papers to different universities based on the number of authors in different universities.

A final difference is that the CHI data follow the CASPAR fields to the letter, whereas the ISI data on papers and citations by university and field appear originally in a more disaggregated form than the biological and medical fields of our regressions. We combined "biology and biochemistry" and "molecular biology and genetics" to form biology. We combined "clinical medicine," "immunology," "neuroscience," and "pharmacology" to form medicine.

The later ISI data contain more measures of scientific output in the universities and fields than the CHI data. There are two measures of numbers of

papers: the number published in a particular year, and the number published over a 5 year moving window. Added to this are two measures of citations to the papers: cumulative total citations to papers published in a particular year through 1993, and total citations to papers published over a 5 year moving window over the course of that window. Each of these output measures has some limitations that stem from the concept and interval of time involved in the measurement. Numbers of papers do not take into account the importance of papers, whereas total citations do. Especially in the larger research programs it is the total impact that matters, not the number of papers, however small. Turning to citations, cumulative cites through 1993 suffer from truncation bias in comparing papers from different years. A paper published in 1991 has only a small part of the citations it will ever get by 1993, whereas a paper published in 1981 has most of them intact. The time series profile of cites will show a general decline in citations, especially in short panels, merely because earlier vintages of papers have decreasing periods in which to draw cites. The second measure available to us--the 5 year moving window of cites to papers published in the same window--is free of this trended truncation bias. However, there is still a truncation bias in the cross section owing to the fact that better papers are cited over a longer period. Thus total cites are to some extent understated in the better programs over the 5 years in comparison to weaker programs. This problem could be gotten around by using a 10-12 year window on the cites, but then we are stuck with one year's worth of data and we would be unable to study trends.

Another point about the data used in the regressions, as opposed to the descriptive statistics, is that they cover an elite sample of top U.S. universities that perform a lot of R&D. The number of universities is 54 in biology, 55 in

chemistry, 53 in mathematics, 47 in medicine, and 52 in physics. These universities are generally the more successful programs in their fields among all universities. Their expenditures constitute roughly half of all academic R&D in each of these areas of research. It turns out that, for the much larger set of universities that we do not include, the data are often missing or else the fields are not represented in these smaller schools in any substantive way. The majority of high impact academic research in the U.S. is in fact represented by schools that are in our samples. Remarkably, and as if to underscore the skewness of the distribution of academic R&D, it is still true that the research programs in our sample display an enormous size range.

Acknowledgments

References

1.   National Science Board (1993) *Science & Engineering Indicators--1993*, (U.S. Government Printing Office, Washington, DC).

2.   Adams, J. D. (1990) "Fundamental Stocks of Knowledge and Productivity Growth," *Journal of Political Economy* 98, 673-702.

3.   Stephan, Paula E. (1995) "An Essay on the Economics of Science," *Journal of Economic Literature*, forthcoming.

4.   Griliches, Z. (1994) "Productivity, R&D, and the Data Constraint" *American Economic Review* 84(1), 1-23.

5.   Jorgenson, D. W. and Fraumeni, B. M. (1992) "The Output of the Education Sector," in Z. Griliches, ed., *Output Measurement in the Service Sectors*, vol. 55 of *NBER, Studies in Income and Wealth* (University of Chicago Press), 303-338.

6.   Rosenberg, N. and Nelson, R. R. (1993) "American Universities and Technical Advance in Industry," CEPR Pub No. 342 (Center for Economic Policy Research, Stanford, CA).

7.   Henderson, R., Jaffe, A. B. and Trajtenberg, M. (1995) "Universities as a Source of Commercial Technology: A Detailed Analysis of University Patenting 1965-1988," NBER working paper #5068, Cambridge, MA.

8.   Katz, S., Hicks, D., Sharp, M., and Martin, B. (1995) *The Changing Shape of British Science* (Science Policy Research Unit, University of Sussex, Brighton).

9.   Levin, R., Klevorick, A., Nelson, R. and Winter, S. (1987) "Appropriating
the Returns from Industrial Research and Development," in M. Baily and
C. Winston, ed., *Brookings Papers on Economic Activity, Special Issue on
Microeconomics* 3(0), 783-820.

10.   Mansfield, E. (1991) "Academic Research and Industrial Innovation,"
Research Policy 20, 1-12.

11.   Mansfield, E. (1995) "Academic Research Underlying Industrial
Innovation: Sources, Characteristics and Financing," *Review of Economics
and Statistics* 77(1), 55-65.

12.   Griliches, Z. (1958) "Research Cost and Social Returns: Hybrid Corn and
Related Innovations," *Journal of Political Economy* 64(5), 419-431.

13.   Nelson, R. R. (1962) "The Link Between Science and Invention: The Case
of the Transistor," in R. R. Nelson, ed., *The Rate and Direction of
Economic Activity* (Princeton University Press, New Jersey).

14.   Weisbrod, B. A. (1971) "Costs and Benefits of Medical Research: A Case
       Study of Poliomyelitis," *Journal of Political Economy* 79(3), 527-544.

15.   Mushkin, S. J. (1979) *Biomedical Research: Costs and Benefits*
       (Ballinger, Cambridge, MA).

16.   Griliches, Z. (1964) "Research Expenditures, Education and the Aggregate
       Agricultural Production Function," *American Economic Review* 54(6),
       961-974.

17.   Evenson, R. E. and Kislev, Y. (1975) *Agricultural Research and
       Productivity* (Yale University Press, New Haven).

18.   Huffman, W. E. and Evenson, R. E. (1994) *Science for Agriculture* (Ames,
       Iowa: Iowa State University Press).

19.   Griliches, Z. (1979) "Issues in Assessing the Contribution of R&D to
       Productivity Growth," *The Bell Journal of Economics* 10(1), 92-116.

20.   Griliches, Z. (1994) "Productivity, R&D, and the Data Constraint,"
      American Economic Review 84, 1-23.

21.   Van Raan, A. F. J. (1988) *Handbook of Quantitative Studies of Science
      and Technology* (North-Holland Press, Amsterdam).

22.   Elkana, Y., Lederberg, J., Merton, R. K., Thackray, A., and Zuckerman, H.
      (1978) *Toward a Metric of Science: The Advent of Science Indicators*
      (Wiley, New York).

23.   Stigler, G. J. (1979) "The Pattern of Citation Practices in Economics,"
      History of Political Economy II, 1-20.

24.   Cole, J. R. and Cole, S. (1973) *Social Stratification in Science* (University
      of Chicago Press).

25.   Price, D. J. de S. (1963) *Little Science, Big Science* (Columbia University
      Press, New York).

26. Adams, J. D. (1993) "Science, R&D, and Invention Potential Recharge: U.S. Evidence," *American Economic Review, Papers and Proceedings* 83(2), 458-462.

27. Pardey, P. G. (1989) "The Agricultural Knowledge Production Function: An Empirical Look," *Review of Economics and Statistics* 71(3), 453-461.

28. Bureau of Economic Analysis, U.S. Department of Commerce (1994) "A Satellite Account for Research and Development," *Survey of Current Business* 74(11), 37-71.

29. National Institutes of Health (1993) "Biomedical Research and Development Price Index," unpublished report (Office of Science Policy and Technology Transfer, NIH, Bethesda, MD).

30. Jankowski, J. (1993) "Do We Need a Price Index for Industrial R&D?" *Research Policy* 22(3), 195-205.

31.   Griliches, Z. (1987) "R&D and Productivity: Measurement Issues and Econometric Results," *Science* 237, 31-35.

Table 1. U.S. Academic Science by Major Field in 1989

Field	Total R&D (mill. dollars)	Number of papers S&EI	Number of papers (UD)* INST100	Citations 5 years (DU)*	Citations per paper 5 years†
Biology	2,638	29,862	28,271	536,453	16.4
Chemistry	608	9,025	10,276	117,403	10.6
Mathematics	214	3,367	3,013	11,231	3.1
Medicine	3,828	34,938	25,885	399,983	13.4
Physics	775	11,392	12,447	150,927	9.8
Subtotal	8,063	88,584	79,892	1,215,997	
All sciences and engineering	15,016	99,215	107,674	1,404,993	

* UD, unduplicated; DU, duplicated paper and citation counts.
† Duplicated citations per duplicated paper.

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Table 2. U.S. Academic Science, Growth Rates, by Selected Field and Total (all fields)
(percent per year)

Field	Total R&D 1979-91		Papers S&EI 1981-91	Papers, INST100 1981-91		Citations 1981-85 to 1989-93	
	SE&I*	BEA†		DU‡	UD‡	DU‡	UDA‡
Biology	5.3	3.1	-1.0	3.7	3.2	7.2	(6.7)
Chemistry	5.0	2.8	2.1	3.6	3.5	4.4	(4.3)
Mathematics	4.2	2.0	-2.3	0.6	0.2	0.5	(0.1)
Medicine	6.1	3.9	1.0	3.2	2.4	5.3	(4.7)
Physics	4.3	2.2	3.9	6.4	5.6	5.9	(5.1)
U.S. Total	5.1	2.9	1.0	3.6	2.8	5.7	(4.9)

* From S&EI, deflated by the GDP deflator.
† Deflated by the BEA R&D deflator.
‡ UD, unduplicated; DU, duplicated counts; UDA, duplicate counts adjusted by the estimated rate of duplication in paper counts.

Table 3. Regression Sample as a Fraction of Total INST 100 Population in 1989, and Growth Rates of Major Variables

Field	Number of universities	Total R&D	Papers	Citations	Growth Rates		
					Total R&D* 1979-91	Papers 1981-91 DU†	5-year citations (81-85)-(89-93) DU†
Biology	54	0.78	.69	.58	2.5	3.7	7.0
Chemistry	55	0.83	.67	.68	2.0	3.7	4.7
Mathematics	53	0.66	.69	.73	2.3	0.6	0.5
Medicine	47	0.69	.58	.58	2.4	3.2	5.1
Physics	52	0.69	.63	.63	0.9	5.5	5.8

* BEA deflator.
† DU, duplicated counts.

Table 4. "Output" Regressions: Coefficient of Lagged 3-Year Average R&D

Coefficients of R&D	Papers (annual)		Pooled cross-sections centered on 1982, 1986, 1990		8-year difference 1990 – 1982	
	CHI 1976-84	INST 100 1981-93	Papers (5 yr)	Citations (5 yr)	Papers	Citations
Biology	.625	.517	.553	.682	.063	.170
Chemistry	.434	.510	.475	.687	.187	.318
Mathematics	.365	.419	.408	.543	.171	.179
Medicine	.717	.582	.625	.711	.015*	−.058*
Physics	.478	.511	.511	.643	.173	.263
Trend			*1989* / *1993*	*1989* / *1993*	*85– 93*	*85– 93*
Biology	.024	.025	.09* / .21	.17 / .41	.04	.06
Chemistry	.015	.022	.07* / .17	.06* / .20	.03	.04
Mathematics	−.023	−.002*	−.00 / −.01*	−.03* / −.11*	.01*	.00*
Medicine	.032	.024	.15 / .23	.19 / .42	.03	.06
Physics	.025	.050*	.23 / .41	.21 / .39	.07	.06

* Not "significantly" different from zero at conventional statistical test levels.

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Table 5. "Output" Regressions: Coefficient of Lagged 3-Year Average R&D or S&Es

Coefficients of R&D or S&Es	*2-Year pooled cross-sections 1982, 1986*					
Output Variables	*Papers (5 yr)*			*Citations (5 yr)*		
Input Variables	*R&D*	*S&Es*	*S&Es, R&D per S&E*	*R&D*	*S&Es*	*S&Es, R&D per S&Es*
Biology	0.64	0.85	0.91, 0.27	0.80	0.96	1.04, 0.45
Chemistry	0.48	0.67	0.68, 0.38	0.71	0.85	0.88, 0.63
Mathematics	0.41	0.88	0.75, 0.26	0.57	1.07	0.86, 0.44
Medicine	0.68	0.67	0.73, 0.55	0.82	0.78	0.86, 0.67
Physics	0.51	0.93	0.85, 0.22	0.65	1.11	0.96, 0.38
Biology & Medicine Combined	0.75	0.68	0.81, 0.59	0.99	0.82	1.03, 0.89

All reported coefficients are statistically "significantly" different from zero at conventional significance levels.

Table 6. Impact of "Window" Length: Citations as a Function of Lagged R&D

	Coefficient of 13-year total 1981	Coefficient of 5-year total 1989	Difference
Biology	.841	.546	.295
Chemistry	.727	.687	.040
Mathematics	.620	.562	.058
Medicine	.881	.574	.307
Physics	.658	.661	-.003
5 fields combined	.970	.889	.081