Creativity-enhancing technological change in the production of scientific knowledge

By: Albert N. Link and John T. Scott

Albert N. Link & John T. Scott (2020) Creativity-enhancing technological change in the production of scientific knowledge, *Economics of Innovation and New Technology*, 29:5, 489-500, DOI: 10.1080/10438599.2019.1636449

Abstract:

We view scientific publications as a measure of technical knowledge. Using the Solow method of functional decomposition and scientific publication data from the National Institute of Standards and Technology, we find that 79% of the increase in scientific publications per unit of scientific personnel is explained by an increase in federal R&D capital per unit of scientific personnel. We describe the unexplained or residual 21% as a measure of creativity-enhancing technological change, a phenomenon that offers a way to reverse the perceived slowing of the productivity of science. The explained 79% offers a possible metric for federal laboratories' mandated reporting of a ROI to federal R&D. Understanding the drivers of the residual 21% could enable public policy to mitigate the resource constraints caused by the breakdown of exponential growth of the resources devoted to science.

Keywords: scientific publications | technological change | R&D | knowledge production function

Article:

I. Introduction

In his seminal article assessing the contribution of R&D to productivity growth, Griliches (1979, 95) footnoted that the relationship between the current state of technical knowledge and investments in R&D might be indicative of a 'knowledge production function.' In the opening decades of the twenty-first century, some evidence suggests a slowdown in the productivity of the processes by which research generates new scientific knowledge. For example, Bloom et al. (2017) present evidence that increasing amounts of scientific resources are required to produce new science, a result that would be expected given the observations of de Solla Price (1963) roughly half a century earlier about the impending breakdown in what had been exponential growth of science.[1] However, creativity-enhancing technological change in the production of scientific knowledge could mitigate or even reverse the slowdown in the productivity of the process generating new science, and it is that type of technological change for which we adduce evidence in this paper. Thus, the purpose of this paper is to decompose the rate of growth in scientific knowledge (scientific output per unit of scientific personnel) into the portion that is explained by an increase in R&D capital per unit of scientific personnel and the residual portion that we attribute to creativity-enhancing technological change.

In Section II, we provide a theoretical framework for the paper in terms of the underlying literature related to scientific knowledge. In Section III, we discuss the data related to scientific publications and investments in R&D that we use in this paper. These data came from the National Institute of Standards and Technology (NIST) within the U.S. Department of Commerce. In Section IV, we implement Solow's approach to decompose the change over time in scientific publications into the portion of that change that is attributable to changes in R&D capital intensity and the portion – the shift in the production function – that remains unexplained by the model. Then, in Section V, we identify an important explanatory factor correlated with the unexplained portion of change over time in scientific publications. In our concluding Section VI, we offer two interpretative points. First, we suggest that the explained portion of the increase in research productivity can be thought of as a rate of return metric for technology transfer activity. Second, we emphasize that the unexplained portion – our calculated residual – can be thought of as a measure of the increase in research creativity enabled by technological change in the process of producing scientific knowledge. Understanding the factors that drive the increase in research creativity is of utmost importance for public policy that successfully supports the continued productivity growth of science even as the exponential growth of scientific inputs is no longer possible.

II. A theoretical framework and related literature

Following Griliches' (1979) description of the R&D to technical knowledge relationship, which he referred to as a knowledge production function, numerous scholars have operationalized the concept in terms of a statistical relationship between patenting activity and investments in R&D. There is a rich literature on the propensity of firms to patent, tracing to Scherer's (1983) classic paper on the propensity to patent and to the scholarship of Bound et al. (1984) and others. Much of the subsequent empirical literature that is couched under the rubric of a knowledge production function is based either on a reduced form model like that used by Scherer (Hall and Harhoff 2012) or a Cobb–Douglas structural model (Hall and Ziedonis 2001; Czarnitzki, Kraft, and Thorwarth 2009) between patent activity and investments in R&D. Link and van Hasselt (2019) apply a structural model to patent applications and public R&D investment across U.S. federal agencies.

---

[1] He observes (1963, 30) that 'the growth curve of science as a whole … has had an extraordinarily long life of purely exponential growth and … at some time must begin to break down and be followed by a generation-long interval of increasing restraint … ' His logic and description of the various logistic curves in his 'Prologue to a Science of Science' (1963, 1–32) predicted that the period of restraint was impending. Indeed, his discussion points to the decades when Bloom et al. (2017) observe declining productivity in science as the period when the exponential growth of science would break down.

The literature also offers the related approach of exploring a knowledge production function in the context of the relationship between scientific publications and R&D investment. In this paper, we develop that related approach to the construction and estimation of a knowledge production function that views scientific publications as a measure of the current state of technical knowledge. The literature that we build on begins with de Solla Price (1963); he used scientific publications as a measure of the growth of science. He observed (de Solla Price 1963, 8):

> Just after 1660, the first national scientific societies in the modern tradition were founded; they established the first scientific periodicals, and scientists found themselves beginning to write scientific papers instead of the books that hitherto had been their only outlets.

The relationship of R&D inputs to the scientific output of publications is explored by Adams and Griliches (1996); they relate the input of academic R&D expenditures to output, across disciplines and over time, as measured by the number of papers published and the number of citations of those papers. Shelton (2008) relates scientific papers, as a measure of science output, to various measures of R&D investment across countries and through time.

A focus on scientific publications is not a criticism of studies with a focus on patenting activity. Rather, publications are an alternative measure of technical output from investments in R&D. To explore the relationship between the input, R&D, and the output, scientific publications, we relate scientific publications to investments in R&D capital and scientific labor through Solow's (1957) method of functional decomposition, which is more general in structure than the models of patenting or publications in the literature.

III. Description of the data

NIST is the U.S. federal laboratory responsible for promoting innovation and industrial competitiveness through the advancement of measurement science, standards, and new technology in ways that enhance economic security and improve our quality of life.[2] The Technology Partnerships Office at NIST is responsible for the summary report to the President and the Congress on annual technology transfers from federal laboratories. While scientific publications are not included in the Office's summary reports as a technology transfer mechanism, NIST has collected data on scientific publications, that appeared as articles in peer-reviewed journals, over time as part of its internal due diligence; and the Office graciously shared those data with us by fiscal year of publication.[3] Herein, we view scientific publications as a measure of the laboratory's scientific knowledge output. See column (1) in Table 1.[4]

---

[2] See, https://www.nist.gov/about-nist/our-organization/mission-vision-values.

[3] We thank Dr. Gary Anderson, then Senior Economist within the Technology Partnerships Office, for graciously sharing these data.

[4] Data on scientific publications were provided from 1973 through 2015; we use the data through 2008. In 2009 and 2010, NIST received funding through the American Recovery and Reinvestment Act of 2009 (ARRA). Thus, post-2008 R&D data and perhaps post-2008 scientific publication data might not be comparable to pre-Great Recession measures. And, transitory fixed effects are not accounted for within the Solow method of decomposition.

Table 1. Data for the Solow decomposition of changes in scientific publications.

Year	**(1) Number Scientific Publications**	**(2) Intramural R&D ($2015,000s)**	**(3) Scientific Personnel Costs ($2015,000s)**	**(4) Research Capital Costs ($2015,000s)**	**(5) Research Capital's Relative Share**	**(6) Index of Scientific Personnel**	**(7) Publications per Index of Scientific Personnel**	**(8) Index of Research Capital**	**(9) Index of Research Capital per Index of Scientific Personnel**	**(10) Δ*A(t)*/*A(t)***	**(11) *A(t)***
1973	417	147267	104306	42961	0.2917	1.0000	417	1.0000	1.0000	0.2272	1.0000
1974	517	148257	106995	41263	0.2783	1.0258	504.0087	0.9605	0.9363	−0.0862	1.2272
1975	466	146277	105918	40359	0.2759	1.0155	458.9095	0.9394	0.9251	−0.0681	1.1215
1976	457	154474	117181	37293	0.2414	1.1234	406.7876	0.8681	0.7727	0.0317	1.0451
1977	493	161743	117336	44407	0.2746	1.1249	438.2531	1.0337	0.9189	0.0365	1.0782
1978	503	159157	116674	42483	0.2669	1.1186	449.6814	0.9889	0.8841	−0.0712	1.1176
1979	492	167397	120678	46719	0.2791	1.1570	425.2517	1.0875	0.9399	0.0724	1.0380
1980	556	176443	126792	49652	0.2814	1.2156	457.3976	1.1557	0.9508	0.1712	1.1131
1981	649	175590	127431	48159	0.2743	1.2217	531.2242	1.1210	0.9176	0.0523	1.3037
1982	689	177380	125260	52120	0.2938	1.2009	573.7402	1.2132	1.0102	0.0742	1.3719
1983	761	182639	126445	56194	0.3077	1.2122	627.7598	1.3080	1.0790	−0.3888	1.4737
1984	450	178873	126216	52657	0.2944	1.2101	371.8847	1.2257	1.0129	0.6692	0.9008
1985	753	181975	123716	58259	0.3201	1.1861	634.8632	1.3561	1.1433	0.0751	1.5036
1986	797	179033	122915	56118	0.3134	1.1784	676.3347	1.3063	1.1085	0.1316	1.6165
1987	861	170463	119745	50718	0.2975	1.1480	749.9879	1.1806	1.0283	−0.0825	1.8292
1988	847	182056	122364	59692	0.3279	1.1731	722.0041	1.3895	1.1844	−0.0073	1.6783
1989	848	183611	122624	60987	0.3322	1.1756	721.3227	1.4196	1.2075	−0.0838	1.6660
1990	791	187114	126332	60782	0.3248	1.2112	653.0903	1.4148	1.1681	0.0747	1.5265
1991	897	197142	135997	61145	0.3102	1.3038	687.9754	1.4233	1.0916	−0.1634	1.6405
1992	789	207196	142613	64583	0.3117	1.3673	577.0679	1.5033	1.0995	−0.0017	1.3723
1993	873	229642	158899	70743	0.3081	1.5234	573.0618	1.6467	1.0809	−0.1003	1.3700
1994	933	271415	179231	92184	0.3396	1.7183	542.9710	2.1458	1.2487	−0.1095	1.2326
1995	952	307575	184690	122886	0.3995	1.7707	537.6549	2.8604	1.6154	0.0319	1.0976
1996	974	304320	195119	109201	0.3588	1.8706	520.6783	2.5419	1.3588	−0.0247	1.1326
1997	976	312584	198374	114210	0.3654	1.9018	513.1862	2.6585	1.3978	0.0445	1.1046
1998	1027	314619	203933	110687	0.3518	1.9551	525.2825	2.5764	1.3178	0.0511	1.1538
1999	1092	317905	210931	106974	0.3365	2.0222	539.9961	2.4900	1.2313	0.1121	1.2127
2000	1181	309428	203475	105953	0.3424	1.9508	605.4072	2.4663	1.2643	−0.2200	1.3487
2001	1043	343094	208665	134429	0.3918	2.0005	521.3681	3.1291	1.5642	0.0033	1.0519
2002	1074	352096	217252	134844	0.3830	2.0828	515.6432	3.1388	1.5070	−0.0574	1.0555

Year	(1) Number Scientific Publications	(2) Intramural R&D ($2015,000s)	(3) Scientific Personnel Costs ($2015,000s)	(4) Research Capital Costs ($2015,000s)	(5) Research Capital’s Relative Share	(6) Index of Scientific Personnel	(7) Publications per Index of Scientific Personnel	(8) Index of Research Capital	(9) Index of Research Capital per Index of Scientific Personnel	(10) $\Delta A(t)/A(t)$	(11) $A(t)$
2003	1065	369088	214317	154771	0.4193	2.0547	518.3261	3.6026	1.7533	0.2310	0.9949
2004	1211	328160	230029	98131	0.2990	2.2053	549.1254	2.2842	1.0358	−0.1320	1.2247
2005	1151	354188	224575	129612	0.3659	2.1530	534.5923	3.0170	1.4013	0.0543	1.0631
2006	1203	351564	217461	134103	0.3814	2.0848	577.0226	3.1215	1.4972	−0.1074	1.1208
2007	1194	388379	227099	161280	0.4153	2.1772	548.4003	3.7541	1.7242	0.0538	1.0004
2008	1235	380177	234211	145966	0.3839	2.2454	550.0074	3.3976	1.5131	−0.1155	1.0542

Notes: All data pertain to fiscal years.

Nominal data for (2) and (3) from NIST; data are converted to $2015 using the GDP deflator.

(4) = (2) – (3).

(5) = (4)/(2).

(6) = (3)/104306.

(7) = (1)/(6).

(8) = (4)/42961.

(9) = (8)/(6).

(10) = Δ(7)/(7) – (5) *x* Δ(9)/(9); to derive the changes for 2008, note that in 2009, (7) and (9) were 514.0144 and 1.7105, respectively.

(11) derived from (10).

Unique to the R&D data provided by NIST is the separation of total intramural R&D into scientific personal costs and the remaining non-scientific personnel or research capital costs. As shown from columns (2) and (3) in Table 1, approximately 60–70% of total intramural R&D has been allocated to personnel each year.

Absent from NIST's assembled data is the number of R&D workers per year.[5] We constructed an annual index of scientific personnel by dividing real scientific personnel costs in each year (column (3)) by real scientific personnel costs in 1973; this index equals 1 for 1973 as shown in column (6). Similarly, we constructed an index of research capital by dividing real research capital costs in each year (column (4)) by real research capital costs in 1973; this index also equals 1 for 1973 as shown in column (8). The data in column (9) represent the ratio of these two indices.

IV. Decomposing changes in scientific publications

Following Solow (1957) in part, let Q denote scientific publications as our proxy for the output of scientific knowledge each year. From each year's total R&D expenditures, let K denote research-capital input, and let L denote scientific-personnel input (i.e. human-capital input). Thus, we write:

$$Q = A(t) f(K, L) \tag{1}$$

where $A(t)$ is a shift factor.[6] In the first year of our time series of observations of Q, K, and L, we assume that $A(1) = 1$, and reflects the impact of accumulated R&D-knowledge stock, both human capital and R&D-physical capital. Then, throughout our time series, it follows that the percentage change in Q equals the percentage change in $A(t)$ plus the percentage changes in K and L where the latter two percentage changes are weighted by their relative shares.[7] From the discrete data in Table 1, we can thus calculate $\Delta A(t)/A(t)$ and $A(t)$, and we do so, as did Solow, under the assumptions that K and L are paid their marginal product and the sum of the two relative shares equals unity.[8]

de Solla Price (1963) documented the exponential growth of science and observed that given the constraints on the growth in the numbers of scientists, the sustainability of the growth of science would require improvements in the process of doing science – technological change in the

---

[5] The Office of Personnel Management reports the number of STEM employees at NIST for the fiscal years beginning in 1998. See, https://www.fedscope.opm.gov/employment.asp.

[6] As Solow (1957, 312) explains, the more general functional form is $Q = F(K,L; t)$. Equation (1) assumes neutral technological change. As with Solow's (1957, 316, see also the discussion at 315) aggregate production function, for the knowledge production function in this paper, $\Delta F/F$ and K/L are uncorrelated, so shifts in the production function for scientific knowledge, as we have measured it, appear to be approximately neutral.

[7] If technological change were not neutral, then (Solow 1957, 313, 315) the analogous relation with $\Delta F/F$ in place of $\Delta A/A$ would be used.

[8] The research portfolio of outputs from NIST's intramural R&D investments logically contains more than scientific publications. We are assuming that the shares of payments to K and L would be the same as their shares in the total unobserved portfolio of research outputs. Stated differently, we are assuming that the scientific publication output behaves the same as would an index of the complete portfolio of research outputs and thus the percentage change over time of scientific publications mimics the percentage change over time of the complete portfolio of research outputs.

process of scientific research.[9] The shift factor *A(t)* reflects that technological change; a positive shift in the knowledge production function measures an increase in the productivity of NIST's scientific research enterprise.

Using our constructed index of scientific personnel, the scientific knowledge output measured as scientific publications per unit of the scientific personnel index increased from 417.0 in 1973 to 550.0 in 2008. Dividing the latter figure by 1.0542, which is the 2008 value for *A(t)* and hence the full shift factor – reflecting, as Solow (1957, 312) emphasizes, the cumulated effects of shifts in the production function over time – for the scientific publications production function in equation (1) over the 36 years, we obtain scientific publications per index unit of the scientific personnel, net of the technological change in the process of scientific research over those years. Thus, (550.0/1.0542) = 521.7 is scientific publications per index unit of scientific personnel if there had been no technological change in the process of scientific research, and [(521.7–417.0)/(550.0–417.0)] = 0.79, or 79% of the increase in scientific publications per index unit of scientific personnel is explained by the increase in research capital per index unit of scientific personnel. Technological change in the process of doing science thus explains [(550.0–521.7)/(550.0–417.0)] = 0.21, or 21% of the increase in the scientific publications per index unit of scientific personnel.[10]

V. A model of creativity-enhancing technological change

The driver of the unexplained 21% might be improvements in the scientific creativity of NIST scientists. If this proposition has merit, then the question arises: What endogenous activities has NIST undertaken to develop such scientific creativity? Or: Are improvements in scientific creativity because of phenomena exogeneous to NIST?

Perhaps future scholars will investigate models, similar to those widely used to measure the marginal rate of return to investments in R&D (Terleckyj 1974), that have worked with functions for the production of aggregate output. In the present context, the models of the production of scientific knowledge might take the form of $\Delta A(t)/A(t) = f(\mathbf{X})$, where $\mathbf{X}$ is a vector of endogenous enhancing activities and exogenous factors. Thus, following Solow (1957), an

---

[9] Reflecting on an impending breakdown in the exponential growth of science after more than 250 years 'during which every half-century science grew out of its order of magnitude,' de Solla Price (1963, 19) observes: 'Scientists and engineers are now a couple of percent of the labor force of the United States, and the annual expenditure on research and development is about the same fraction of the Gross National Product. It is clear that we cannot go up another two orders of magnitude as we have climbed the last five. If we did, we should have two scientists for every man, woman, child, and dog in the population, and we should spend on them twice as much money as we had.' de Solla Price (30) offers 'a counsel of hope rather than despair. … [W]e have the beginning of new and exciting tactics for science, operating with quite new ground rules.'

[10] Alternatively, from Table 1, scientific publications per $100,000 of real personnel costs increased from 0.400 publications per $100,000 in personnel costs in 1973 to 0.527 in 2008 when the Great Recession began. Dividing the latter figure by 1.0542, which is the 2008 value for *A(t)* and hence the full shift factor for the knowledge production function in equation (1) over the 36 year period, we have scientific publications per $100,000 of personnel costs net of the technological change in the process of scientific research over the 36 years. Since (0.527 / 1.0542) = 0.500, we see that without the improvement in the process of scientific research, the increase in research capital per unit of scientific personnel explains 79 percent of the actual increase in scientific publications per $100,000 in scientific personnel costs. Technological change in the process of doing science explains 21 percent of the increase in the scientific publications per unit of personnel costs.

understanding of those factors could be developed by studying the time series for *A(t)*. The importance of such a study follows from de Solla Price's observations about the growth of science and the inference that we need productivity-enhancing technological change in the production of scientific knowledge.

The work for future scholars is important because of the need for productivity-enhancing technological change as the proportion of the workforce devoted to science inevitably ceases to grow exponentially. It is also important because we do not understand the endogenous and exogenous factors at work that drive the dramatic swings in creativity observed in the time series for *A(t)* that we have developed to reflect the shifts in the function describing scientific publications as a function of NIST's use of scientific resources.

Figure 1 depicts the time series of *A(t)*; the final data point in the plot of *A(t)* through time reflects the full, cumulative effect of the shifts in the knowledge production function over the 36 years that we have examined. That full, cumulative shift was used in Section IV to identify the increase in knowledge attributable to technological change in the production of scientific knowledge. But, unlike Solow, who could look at his plot (Solow 1957, Chart 3, 313) of *A(t)* in the context of his aggregate production function and observe (316), 'One notes with satisfaction that the trend is strongly upward … ', we are confronted with a puzzle. Figure 1 shows what appears to be a systematic advance over the period from 1973 through 1987 in technological change for NIST's production of scientific knowledge using its research capital and personnel. This systematic advance is not without interruptions. The number of scientific publications declined in 1984 and then increased in 1985, and given lags in the publication process this might have been the result of endogenous events in earlier years, or it might simply be unexplained anomaly. However, the positive shift in the production function from 1973 through 1987 was followed by a decline – unexplained by the changes in the intensity of research capital.

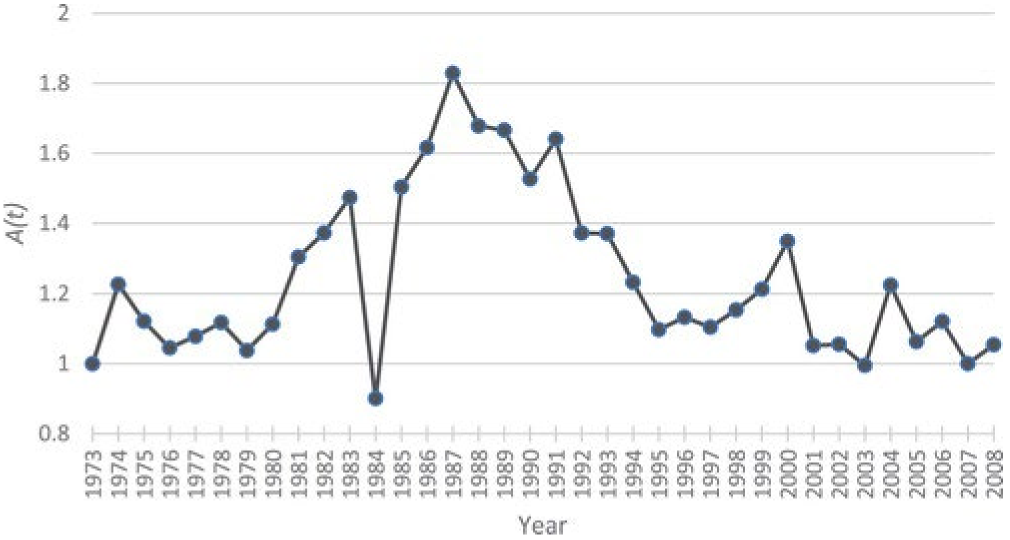

Figure 1. The Shift Factor, *A(t)*.

One possible explanation of the puzzle posed by the downward shifts in the knowledge production function that began in 1988 would be the onset of a period of institutional change as the National Bureau of Standards (NBS) became NIST in that year. Director Ernest Ambler had served as the director of NBS since 1975, and he presided over the institutional change from NBS to NIST in 1988, and a new director took over the leadership of NIST in 1990. From then throughout the remainder of our time series, the turnover of NIST directors was much more frequent.[11]

We can describe the change in the knowledge production function in the NBS years, as contrasted with the NIST years, by using a model of shifts in the production of scientific knowledge. As discussed above, the model takes the form of $\Delta A(t)/A(t) = f(\mathbf{X})$, where $\mathbf{X}$ is a vector of endogenous enhancing activities and exogenous factors. Here, our illustrative model is presented as one with the annual rate of change in the shift factor being a function of whether the national laboratory was organized as the old NBS or as the newly structured NIST, and also a variable *Director's_Tenure* that measures, for each year, the amount of time prior to that year that NIST's Director had held the position. Additionally, we introduce the product of the two variables to allow for different slopes as well as different intercepts in the estimated relationship for the periods with the federal laboratory as NBS and then as NIST. Thus, there are three explanatory variables: *dNIST*, *Director's_Tenure*, and the interaction of the two variables. *dNIST* is a qualitative variable that equals 1 for each year from 1988 through the final year of the data in 2008, years when the federal laboratory was NIST; it equals 0 for the years from 1973 through 1987, the years when the federal laboratory was the NBS. *Director's_Tenure* is measured from the information in Table 2.[12] Table 3 shows the 36 yearly observations for *Director's_Tenure*. Table 4 shows the descriptive statistics for these variables.

Table 2. Directors of the National Bureau of Standards (until 1988) and the National Institute of Standards and Technology (from 1988).

Director	**Time Period**
Lewis M. Branscomb	1969–1972
Richard W. Roberts	1973–1975
Ernest Ambler	1975–1989
John W. Lyons	1990–1993
Arati Prabhakar	1993–1997
Raymond G. Kammer	1997–2000
Karen Brown (acting director)	2000–2001
Arden L. Bement Jr.	2001–2004
Hratch Semerjian (acting director)	2004–2005
William A. Jeffrey	July 2005 – August 2007
James M. Turner (acting director and deputy director)	September 2007 – September 2008
Patrick D. Gallagher (deputy director)	September 2008 – November 2009

Source: https://www.nist.gov/director/pao/directors-national-bureau-standards-1901–1988-and-national-institute-standards-and

---

[11] See, https://www.nist.gov/director/pao/directors-national-bureau-standards-1901-1988-and-national-institute-standards-and.

[12] *Director's_Tenure* is, for each year, the number of previous years NIST's Director had held the position. In years where the new director assumed control during the year, for that transition year the tenure of the outgoing director is recorded. Then, in the next year the tenure for the new director is recorded as 1. When a new director begins tenure at the outset of the year, for that year the tenure is recorded as 0 (the director has had no experience in the position prior to the year), and then it is 1 in the next year.

Table 3. Yearly observations on *Director's_Tenure*.

Year	Director's_Tenure	Year	Director's_Tenure
1973	0	1991	1
1974	1	1992	2
1975	2	1993	3
1976	1	1994	1
1977	2	1995	2
1978	3	1996	3
1979	4	1997	4
1980	5	1998	1
1981	6	1999	2
1982	7	2000	3
1983	8	2001	1
1984	9	2002	1
1985	10	2003	2
1986	11	2004	3
1987	12	2005	1
1988	13	2006	1
1989	14	2007	2
1990	0	2008	1

Table 4. Descriptive statistics for the variables ($n = 36$).

Variable	Mean	Standard Deviation	Minimum	Maximum
$\Delta A(t)/A(t)$	.0105083	.1666539	−.3888	.6692
dNIST	.5833333	.5	0	1
Director's_Tenure	3.944444	3.927518	0	14
*dNIST*Director's_Tenure*	1.694444	3.124278	0	14

Table 5 shows the results from the estimated model. The first specification fits a different intercept and different slope for the growth rate of the shift in the production function for each organizational period; that is, during the period when the federal laboratory was organized as the NBS, and then during the period of NIST. The difference in the intercepts is wholly insignificant, and the model as a whole is not quite significant at the .10-level. Given that the difference in the intercepts for the two periods is completely insignificant, the second specification provides the parsimonious functional form with just the slopes of the relationship differing, and that specification is statistically significant at the .05- level. The partial derivative of $\Delta A(t)/A(t)$ with respect to *Director's_Tenure* is positive (with the rate of change in the shift factor increasing about 1% per year per year of tenure for both specifications) during the period of the NBS when there was very little turnover in the director's position. That derivative falls and indeed becomes slightly negative (about minus 0.3% for the first specification, and about minus 0.4% for the second) during the NIST period when there was considerable turnover of directors. The partial derivative of $\Delta A(t)/A(t)$ with respect to *dNIST* is negative in both specifications and even becomes more negative as the tenure of a director during the period beginning in 1988 increases. No director served for very long within that period, and if one takes the estimate at face value, it appears that challenges – to the extent that they were manifested in our measure of scientific output – of the reorganization from NBS to NIST were not mitigated by longer tenure. However, it may simply be that although our specification using *Director's_Tenure* captures the period of upward shifts in the production function that is then followed by a period of downward shifts, the behavior of $\Delta A(t)/A(t)$ may have a different explanation. Rather than a period of adjustment to the new organizational form for the national laboratory, the downward shift in the production function may reflect the period of adjustment that de Solla Price predicted, and we return to that possibility in our conclusion.

Table 5. Illustrative estimation of $\Delta A(t)/A(t) = f(\mathrm{X})$ ($n = 36$).

Prais-Winsten Regression for First-order Autocorrelation, Iterated Estimates
Dependent variable $\Delta A(t)/A(t)$

	(1)	**(2)**
Variable	Coefficient (standard error) [probability > |t|]	
dNIST	– 0.0177	
	(0.0569)	
	[0.758]	–
Director's_Tenure	0.00958	0.0112
	(0.00727)	(0.00506)
	[0.197]	[0.034]
*dNIST*Director's_Tenure*	– 0.0127	– 0.0152
	(0.0107)	(0.00694)
	[0.244]	[0.036]
constant	0.00341	– 0.00907
	(0.0475)	(0.0251)
	[0.943]	[0.720]
F(d.f.)	F(3, 32) = 2.20	F(2, 33) = 3.34
(probability > F)	(0.108)	(0.0478)
R^2	0.171	0.168
rho	– 0.465	– 0.465
Durbin-Watson statistic: original	2.85	2.84
Durbin-Watson statistic: transformed	2.08	2.08

VI. Conclusion

The contribution of this paper is our decomposition of the rate of growth in scientific output per unit of scientific personnel into the portion that is explained by an increase in R&D capital per unit of scientific personnel and the residual portion that we attribute to creativity-enhancing technological change. Using Solow's method, we found that 79% of NIST's increase from 1973 to 2008 in scientific publications per unit of scientific personnel is explained by an increase in federal R&D capital per unit of scientific personnel. In conclusion, we observe first that the explained 79% offers a possible metric for federal laboratories' mandated reporting of the ROI to federal R&D. Then, second, we observe that the unexplained or residual 21% – a measure of creativity-enhancing technological change – is a phenomenon that offers a way to reverse the perceived slowing of the productivity of science.

The mandated reporting about the results of federal R&D reflects the importance of technology transfers from federal laboratories. Those technology transfers gained prominence with the passage of the Stevenson-Wydler Technology Innovation Act of 1980 (Public Law 96-480):

> It is the continuing responsibility of the Federal Government to ensure the full use of the results of the Nation's Federal investment in research and development. To this end the

> Federal Government shall strive where appropriate to transfer federally owned or originated technology to State and local governments and to the private sector. …

While there were amendments to the Stevenson-Wydler Act and other intervening legislation to improve technology transfer from federal laboratories, the importance of technology transfer was highlighted again by President Barack Obama in his 2011 Presidential Memorandum – Accelerating Technology Transfer and Commercialization of Federal Research in Support of High-Growth Businesses:

> One driver of successful innovation is technology transfer, in which the private sector adapts Federal research for use in the marketplace. … I direct that [Federal laboratories] establish goals and measure performance, streamline administrative processes, and facilitate local and regional partnerships in order to accelerate technology transfer and support private sector commercialization.

Most recently, President Donald Trump, in his President's Management Agenda (undated, 49), noted:

> The Federal Government invests approximately $150 billion annually in research and development (R&D) conducted at Federal laboratories, universities, and other research organizations. For America to maintain its position as the leader in global innovation, bring products to market more quickly, grow the economy, and maintain a strong national security innovation base, it is essential to optimize technology transfer and support programs to increase the return on investment (ROI) from federally funded R&D.

Scientific publications are a federal laboratory transfer mechanism for technical knowledge. Although our analysis in this paper only deals with scientific publications from one federal laboratory, NIST, our finding that 79% of the increase in scientific publications per index unit of scientific personnel is associated with the increase in R&D-based research capital per index unit of scientific personnel is a measure of the return on intramural R&D investments in scientific knowledge.

What is also interesting is that 21% of the increase in scientific publications per index unit of scientific personnel is not explained by investments in R&D-based research capital per index unit of scientific personnel. Of course, one could reasonably argue that our calculated residual does not take into account improvements in human capital over time, say though education; or lags between investments in R&D-based research capital and the output from the publication process; or elements of the depreciation of R&D-based knowledge. We do not dismiss such arguments. However, what we have documented is that R&D investments are not the end-all explanation for the generation of new scientific knowledge made public through scientific publications from R&D; there is a residual increase in scientific knowledge, unexplained by the increase in research capital per unit of research personnel. That increase, we suggest, would be because of creativity-enhancing technological change in the process of producing scientific knowledge. Although we have examined only scientific publications as a measure of knowledge, and although we have studied the knowledge production at NIST, the approach that we have used could be applied to other measures of knowledge production and for other research organizations such as universities.

Moreover, the downward shifts in the knowledge production function that began in 1988 may reflect the effects of exponential growth of science beginning to ‘break down’ and the ‘interval of increasing restraint’ predicted by de Solla Price (1963, 30) as discussed earlier. If so, the decline after 1987 in $A(t)$ as depicted in Figure 1 would correspond to the general decline in productivity in science described by Bloom et al. (2017), rather than simply reflecting a period of institutional readjustment at NIST that we modeled in Section V using an illustrative model in the form of $\Delta A(t)/A(t) = f(\mathbf{X})$.

Perhaps of more general importance for public policy aimed at supporting the continued growth of science, even as exponential growth of scientific inputs is no longer possible, is that our decomposition identified creativity-enhancing technological change and factors that drive it. Perhaps future research will develop understanding of the endogenous enhancing activities and the exogenous factors in the creation of scientific knowledge, not only within NIST but also across other federal laboratories and, moreover, across universities as well as the basic research activities of industry. Understanding creativity-enhancing technological change in the production of scientific knowledge may suggest adjustments to policy that would have the potential to increase productivity in science.

Acknowledgement

We thank an anonymous reviewer and Cristiano Antonelli for helpful comments and suggestions on an earlier version of this paper.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Adams, James, and Zvi Griliches. 1996. “Measuring Science: An Exploration.” *Proceedings of the National Academy of Sciences of the United States of America* 93: 12664–12670. doi: 10.1073/pnas.93.23.12664

Bloom, Nicholas, Charles I. Jones, John Van Reenen, and Michael Webb. 2017. “Are Ideas Getting Harder to Find?” NBER Working Paper 23782, NBER Working Paper Series, National Bureau of Economic Research.

Bound, John, Clint Cummins, Zvi Griliches, Bronwyn H. Hall, and Adam Jaffe. 1984. “Who Does R&D and Who Patents?” In *R&D, Patents, and Productivity*, edited by Z. Griliches, 21–54. Chicago: University of Chicago Press for the National Bureau of Economic Research.

Czarnitzki, Dirk, Kornelius Kraft, and Susanne Thorwarth. 2009. “The Knowledge Production of ‘R’ and ‘D’.” *Economics Letters* 105: 141–143. doi: 10.1016/j.econlet.2009.06.020

de Solla Price, Derek J. 1963. *Little Science, Big Science*. New York: Columbia University Press.

Griliches, Zvi. 1979. “Issues in Assessing the Contribution of Research and Development to Productivity Growth.” *Bell Journal of Economics* 10: 92–116. doi: 10.2307/3003321

Hall, Bronwyn H., and Dietmar Harhoff. 2012. “Recent Research on the Economics of Patents.” *Annual Review of Economics* 4: 541–565. doi: 10.1146/annurev-economics-080511-111008

Hall, Bronwyn H., and Rosemarie H. Ziedonis. 2001. “The Patent Paradox Revisited: An Empirical Study of Patenting in the U.S. Semiconductor Industry, 1979–1995.” *RAND Journal of Economics* 32: 101–128. doi: 10.2307/2696400

Link, Albert N., and Martijn van Hasselt. 2019. “A Public Sector Knowledge Production Function.” *Economics Letters* 175: 64–66. doi: 10.1016/j.econlet.2018.12.025

Scherer, Frederic M. 1983. “The Propensity to Patent.” *International Journal of Industrial Organization* 1: 107–128. doi: 10.1016/0167-7187(83)90026-7

Shelton, Robert D. 2008. “Relations between National Research Investment and Publication Output: Application to an American Paradox.” *Scientometrics* 74: 191–205. doi: 10.1007/s11192-008-0212-2

Solow, Robert M. 1957. “Technical Change and the Aggregate Production Function.” *The Review of Economics and Statistics* 39: 312–320. doi: 10.2307/1926047

Terleckyj, Nestor E. 1974. *The Effects of R&D on the Productivity Growth of Industries: An Exploratory Study*. Washington, DC: National Planning Association.