# Research Productivity Over the Life Cycle: Evidence for Academic Scientists

Sharon G. Levin; Paula E. Stephan

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# Research Productivity Over the Life Cycle: Evidence for Academic Scientists

*By* SHARON G. LEVIN AND PAULA E. STEPHAN *

*The relationship between age and the publishing productivity of Ph.D. scientists is analyzed using data from the* Survey of Doctorate Recipients *(National Research Council) and the* Science Citation Index. *The longitudinal nature of the data allows for the identification of pure aging effects. In five of the six areas studied, life-cycle aging effects are present. Only in particle physics, where scientists often speak of being on a "religious quest," is there indication that scientific productivity is not investment-motivated. Vintage effects are also considered. The expectation that the latest educated are the most productive is not generally supported by the data.* (*JEL* 022, 821, 841, 851)

Research productivity over the life cycle has become an increasingly important topic to the American scientific community as the average age of scientists affiliated with institutions of higher learning has increased.[1] A popular belief held by scientists and the lay public alike is that science is a young person's game. Karl F. Gauss was 18 when he developed least-squares, Charles R. Darwin was 29 when he developed the concept of natural selection, Albert Einstein was 26 when he formulated the theory of relativity, and Sir Isaac Newton was 24 when he began his work on universal gravitation, calculus, and the theory of colors (Stephen Cole, 1979).

This paper examines the research productivity of scientists over the life cycle. We develop a model of scientific productivity in which scientists engage in research not only for the present value of the stream of future financial rewards associated with research, but also for the current satisfaction that research provides the scientist. The model is estimated with a unique pooled cross-section longitudinal data base[2] created from the National Research Council's biennial 1973–1979 *Survey of Doctorate Recipients* (SDR) for scientists at Ph.D.-granting institutions trained in six subfields of physics and earth science.

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*Department of Economics, University of Missouri-St. Louis, St. Louis, MO 63121; and Policy Research Program and Department of Economics, Georgia State University, Atlanta, GA 30303, respectively. This work was supported by funds from the Alfred P. Sloan Foundation (B1983-43), the Exxon Education Foundation, and the National Science Foundation (grant no. SRS 8306947). Additional resources were provided by the Graduate School and Gerontology Program of the University of Missouri-St. Louis and the Georgia State University Research Office and College of Business Administration Research Council. All opinions expressed are those of the authors and not the granting institutions. We thank George Boyce and Sue Henn of the National Research Council for their assistance in putting together the data base. In addition to the individuals mentioned in Appendix A, we also acknowledge the help of Michael Pogodzinski, Rubin Saposnik, Frank Stafford, Lester Taylor, and members of the Emory University-Georgia State University Seminar. Graduate research assistants on the project were Robert Eisenstadt, Stacy Kottman, Jan Luytjes, and Yan Liao. Finally, we acknowledge the helpful comments of three anonymous referees.

[1] Between 1968 and 1978, the proportion of young doctorates (those who received a degree in the past seven years) among science and engineering full-time faculty declined from about 43 percent to 26 percent (National Research Council, 1979 p. 26). Between 1975 and 1985, the proportion of doctoral scientists under 35 years of age engaged in teaching declined from 24 percent to 9 percent, while the proportion over 55 years of age increased from 14 percent to 24 percent (National Science Foundation, 1988 p. 44).

[2] The data base resides with the Data Processing Unit of the Office of Scientific and Engineering Personnel at the National Research Council (NRC). Upon request, we will provide the documentation necessary for replication. Use of the data base by researchers for purposes other than replication will likely require obtaining permission from the National Academy of Sciences and the Institute of Scientific Information, given the terms of a lease agreement signed in 1983.

The results support an investment model of scientific productivity. In five of the six areas, life-cycle aging effects are present. Only in particle physics, where scientists are often portrayed as on a "religious quest," is there any indication that scientific productivity is not investment-motivated. Assuming that demand conditions do not change markedly, these results suggest that the American scientific community over the next 10 or 15 years may not be as productive as a younger community was in the 1960's and early 1970's.

Section I presents a conceptual model of scientific productivity, incorporating both the investment and consumption motives noted above. Section II sets forth the methodology and specification used to estimate the model. Section III presents the results, and the conclusions follow in Section IV.

## I. A Conceptual Framework

Two hypotheses are commonly advanced for scientists engaging in research. One focuses on research as investment-motivated, arguing that scientists engage in research because of the future financial rewards associated with the activity; the other focuses on research as consumption-motivated, downplaying the importance of financial rewards and stressing instead the scientist's fascination with the research puzzle itself. "Research is in many ways a kind of game, a puzzle-solving operation in which the solution of the puzzle is its own reward" (Warren Hagstrom, 1965 p. 16). Although the investment motive implies a decline in research productivity over the career, given the finite time horizon (Arthur Diamond, 1984), the consumption motive does not. The model set forth below incorporates both the investment and consumption motives for research.

(i) The individual chooses to allocate time between two activities, research and nonresearch, such as teaching and consulting, which produces current income.

(ii) The objective of the scientist is to allocate time in such a way as to maximize utility, $U_t$, over a career which begins at time zero, after receipt of the Ph.D., and ends at time $T$, the day of retirement. Utility is a function of research output, $R_t$, and market goods, $X_t$, which cost a constant price, $p$. Thus, the problem is to choose $s_t$, the proportion of time engaged in producing research, so as to maximize

$$(1) \qquad J = \int_0^T e^{-\rho t} U(R_t, X_t)\, dt$$

$$= \int_0^t e^{-\rho t} \ln\left(R_t^{\Theta_1} X_t^{\Theta_2}\right) dt$$

$$\Theta_1, \Theta_2 > 0.$$

We assume that $T$ is known and, following Harl Ryder et al. (1976), also that $\rho$, the time-preference parameter, is zero. This particular utility function has been widely used in demand analysis (e.g., Robert Pollak and Terrence Wales, 1969; Ryder et al., 1976). Further, because of the high acceptance rates in science (Carnot Nelson and Dennis Pollock, 1970; A. Carolyn Miller and Sharon Serzan, 1984), we make the simplifying assumption that all research output is published.

(iii) Although publications do not wear out, their relevance does, as change occurs in the field. Thus, changes in the stock of publications deemed relevant, $P_t$, is given by

$$(2) \qquad \dot{P}_t = R_t - \delta P_t$$

where $\delta$ is a depreciation rate and the dot denotes the derivative with respect to time.

(iv) Income in any time period is a function of $P_t$. Previous publications that are no longer valued by the field do not contribute to current income, $I_t$, where $I_t = \alpha(1 - s_t)P_t$ and $\alpha$ is the rental value of a unit of $P$.

(v) The change in assets, $A$, over time, is given by

$$(3) \qquad \dot{A}_t = -pX_t + \alpha(1 - s_t)P_t + rA_t$$

where $r$ is the interest rate.

(vi) A by-product of producing research is learning. Because most research has non-human-capital-enhancing aspects, only $h$

proportion of the research output that is produced at time $t$ is incorporated into the individual's stock of knowledge. As a result, $K_t$, the scientist's effective knowledge (knowledge that is "up to date") equals $hP_t$.

(vii) Research output is produced by combining effective knowledge with time

$$(4)\quad R_t = f(s_t K_t) = A_1(s_t h P_t)^\beta \qquad \beta < 1,\ A_1 > 0.$$

This production function has a long tradition in human capital studies (e.g., Yoram Ben-Porath, 1967; Ryder et al., 1976; Stephan, 1976; John McDowell, 1982; Diamond, 1984).

With the problem as formulated in (i)–(vii), a dynamic model is necessary. In terms of control theory, the Hamiltonian takes the form

$$(5)\quad H = \ln R_t^{\Theta_1} + \ln X_t^{\Theta_2} + \lambda_{P_t}\left(A_1 s_t^\beta h^\beta P_t^\beta - \delta P_t\right) + \lambda_{A_t}\left[-pX_t + \alpha(1-s_t)P_t + rA\right]$$

where $\lambda_A$ and $\lambda_P$ represent the shadow values of assets and effective publications, respectively. The necessary conditions for a maximum are to let $\hat{s}_t$ and $\hat{X}_t$ be control variables that maximize the objective function, subject to the conditions given by (2), (3), and (4), some initial stock of articles (coauthored, as is the custom in science, with advisors while in graduate school), and some initial stock of assets.[3] Then, $\hat{s}_t$ and $\hat{X}_t$ maximize the Hamiltonian, and the shadow prices satisfy the equations

$$(6)\quad \dot{\lambda}_{P_t} = -\partial H/\partial P_t = -\beta\Theta_1/P_t - \left(\lambda_{P_t}\beta R_t\right)/P_t + \delta\lambda_{P_t} - \lambda_{A_t}\alpha(1-s_t)$$

$$(7)\quad \dot{\lambda}_{A_t} = -\partial H/\partial A_t = -r.$$

The optimal path is the solution to the differential equations in $A$, $P$, $\lambda_P$, and $\lambda_A$ satisfying the transversality conditions that

$$(8)\quad \lambda_{P_T}P_T = 0 \qquad \left(P_T = \text{free},\ \lambda_{P_T} = 0\right)$$

and

$$(9)\quad \lambda_{A_T}A_T = 0 \qquad \left(A_T = 0,\ \lambda_{A_T} = \text{free}\right).$$

Assuming that $r = 0$ in order to simplify the problem, it follows that $\lambda_{A_t}$ is constant over time.

Maximizing the Hamiltonian with respect to $X$ yields the result that market goods consumed by the individual are constant over time:

$$(10)\quad \hat{X}_t = \Theta_2/\lambda_A p$$

where the caret denotes the optimal value. Maximizing the Hamiltonian with respect to $s$ and substituting the value of $s$ into (6) yields

$$(11)\quad \dot{\lambda}_{P_t} = \delta\lambda_{P_t} - \lambda_A\alpha.$$

Given the transversality conditions, this implies that

$$(12)\quad \lambda_{P_t} = (\lambda_A\alpha/\delta)\left[1 - e^{-\delta(T-t)}\right]$$

and

$$(13)\quad \hat{R}_t = A_1\left[\Theta_1 E + (h\beta/\delta) \times \hat{R}_t\left(1 - e^{-\delta(T-t)}\right)\right]^\beta$$

where $E = [h\beta/(\lambda_A\alpha)] > 0$. Thus, in this model, $\hat{R}_t > 0$, even at time $T$, the date of retirement, when $\hat{R}_T = A_1[\Theta_1 E]^\beta$.

Although there is no known solution for equation (13), two propositions can be derived.

PROPOSITION 1: *Research activity is greater, the greater is the taste for research,* $\Theta_1$:

$$(14)\quad \frac{\partial \hat{R}_t}{\partial \Theta_1} = \frac{\beta \hat{R}_t E}{\Theta_1 E + X} > 0 \qquad \text{for } t < T$$

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[3] There are, of course, two stages to this problem. The first stage is one of complete specialization in research and is characterized by $s_t = 1$. In the second stage, the time constraint is not binding. Here, we focus on the second stage and assume that the scientist stays in graduate school until ready to pass from stage 1 to stage 2. If, however, $\Theta_2 = 0$, the scientist never is motivated to earn income, and stage 1 persists for the duration of the career.

*where* $X=(h\beta/\delta)R_t(1-\beta)(1-e^{-\delta(T-t)})>0$ *for all* $t<T$ *and* $X=0$ *for* $t=T$.

The sociology-of-science literature makes the argument that this taste for research is learned in graduate school. Moreover, interviews with scientists suggest that this taste is field-dependent, with scientists in some fields placing greater value on the satisfaction derived from engaging in research than do scientists in other fields.

PROPOSITION 2: *Research activity declines over the life cycle*:

$$(15)\qquad \dot{\hat{R}}_t=\frac{(-\beta^2\hat{R}^2h)e^{-\delta(T-t)}}{\Theta_1E+X}<0 \qquad \text{for } t<T.$$

Furthermore, although it is not possible to prove, simulations of the model support the concept that larger values of $\Theta_1$, the taste for research, generate flatter research profiles. This has some intuitive appeal. Early in the career, the strong investment incentive for research complements a scientist's puzzle-solving urge, but as the scientist ages and the present value of the investment benefit declines, the scientist must supplement the investment component to meet the puzzle-solving need. Clearly, this is more important the larger is $\Theta_1$.[4]

## II. Methodology

Research productivity over the life cycle has received little attention in the economics literature, although there have been several related studies in other disciplines (e.g., Harvey Lehman, 1953; Paul Allison and John Stewart, 1974; Alan Bayer and Jeffrey Dutton, 1977; Harriet Zuckerman, 1977; Stephen Cole, 1979; Allison et al., 1982; Diamond, 1986). To date, the empirical evidence on the life-cycle effect is weak and largely inconclusive, because most studies use cross-sectional data. Since scientists of different ages come from different cohorts in a cross-sectional study, aging effects are confounded with cohort effects.

One type of cohort effect is associated with change in the knowledge base of the scientist's field. Because of what Jacob Mincer (1974 p. 21) calls the "secular progress of knowledge," there is a general presumption in science that the latest educated are the best educated. We incorporate this concept by making the depreciation rate in the model ($\delta$) vintage-dependent, so that successively later cohorts face lower and lower depreciation rates as science progresses toward a more complete understanding of the "laws" governing the universe.[5] Thus, the stock of relevant articles (2) declines more rapidly for scientists coming from earlier vintages than for scientists coming from later vintages. Since

$$(16)\qquad \frac{\partial\hat{R}_t}{\partial\delta}=(\beta\hat{R}_t/\delta)^2h\times\frac{(e^{-\delta(T-t)})(\delta(T-t)+1)-1}{\Theta_1E+X}<0$$

for all $t<T$, it follows that $\partial\hat{R}_t/\partial V>0$, where $V$ stands for the date of the Ph.D.[6]

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[4] Two special cases in which a utility parameter is zero are also of interest. First, when $\Theta_1=0$ and the scientist derives no satisfaction from engaging in research, the path of $R_t$ is the same as the path in a simplified Ben-Porath income-maximizing model. In this case, $R_T=0$, and the simulations suggest that the $R_t$ profile is steeper than when $\Theta_1>0$. Second, when $\Theta_2=0$ and market goods provide no satisfaction, the scientist lacks the motivation to earn income and remains in the stage of complete specialization throughout the career (see footnote 3). In this situation, $s_t=1$, and research is constrained only by the amount of effective knowledge available to the scientist. Thus,

$$R_t=A_1(hP_t)^\beta \quad\text{and}\quad \dot{R}_t=\beta R_t/P_t[R_t-\delta P_t].$$

It follows in this case that, as long as $R_t>\delta P_t$, research increases with career age. Simulations suggest that $R_t>\delta P_t$ for a period longer than a normal career for reasonable values of $P_0$, $A_1$, $\beta$, and $h$.

[5] Clearly, this is a simplified view of how change in knowledge affects a scientist's stock of relevant publications. One might expect, for example, that the earliest articles authored by a scientist would be the first to be rendered obsolete.

[6] Previous work in human capital (Solomon Polachek, 1976; McDowell, 1982; Stephan and Levin, 1983) has examined variation in the rate at which knowledge becomes obsolete across academic fields or

Another factor that affects research productivity and varies by cohort is the state of the job market at the time the doctorate is received. The link in this instance between productivity and cohort is the strong evidence that research output is affected not only by attributes of the scientists but also by attributes of the employing institutions (J. Scott Long, 1978; Gerald Cole, 1979; Long and Robert McGinnis, 1981). Consequently, scientists graduating when appointments in the top academic sector are few and far between are expected to be less productive over their lives than are scientists who have the good fortune to leave graduate school when the prospects for employment in the top sector are good.

Finally, in addition to differences in the rate at which knowledge becomes obsolete and differences in opportunities that greet different cohorts over time, cohorts may vary in the levels of ability or motivation they bring to the fields or specialty areas they enter. Whether or not this occurs depends in part upon the desirability of other fields or professions relative to the one in question at the time the career decision is made. In recent years, this may have become a significant factor in science given the surge of interest in the high-salaried professions of business, law, and applied science. As a consequence, it is possible that these areas were able to secure a disproportionate share of the best minds from later cohorts, leaving some areas of science with a relative "brain drain."[7]

One way to control for vintage and these other cohort-related effects is to follow a single cohort over time. However, this approach ignores the fact that the scientific "state of the arts" and the work environment change over time. Thus, these calendar-time effects may also obscure the relationship between research productivity and age.

In this study, we develop a pooled cross-section time-series data base which permits us to control for cohort as well as for calendar time. The data base was created by matching records from the National Research Council's biennial 1973–1979 *Survey of Doctorate Recipients* (SDR) with publishing information from the *Science Citation Index* (SCI) prepared by the Institute of Scientific Information (ISI).[8] (Details are provided in Appendix A). Four measures of research output were created. PUB1 measures straight publication counts occurring over a two-year period. PUB2 adjusts these counts for coauthorship. PUB3 uses Eugene Garfield's (1976) impact factor (ISI) to adjust for journal quality, while PUB4 adjusts the straight counts for both coauthorship and quality.

Although the data base was initially assembled for scientists trained in biochemistry, earth science, physics, and plant and animal physiology, the econometric investigation focused on six areas: solid-state/condensed-matter physics, particle physics, atomic and molecular physics, oceanography, geophysics, and geology.[9] Subfield analyses were conducted because publishing patterns vary significantly across fields and subfields and the identification of vintage effects is feasible only at the subfield or specialty level. For each subfield, a case study identified vintage as well as other cohort effects (see Appendix A).

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occupations and the consequences of this variation for investment over the life cycle as well as for career choice. While recognizing that rates of obsolescence vary across disciplines, here we focus on the idea that knowledge acquired during graduate school is more durable for later vintages than for earlier vintages, based on the assumption that science progresses towards "truth." Clearly, other issues may fall under the rubric of obsolescence (e.g., the distinction between anticipated obsolescence and unanticipated obsolescence and whether unanticipated change impacts relatively more on younger than on older scientists). Given our focus on aging, such issues are outside the scope of this article.

[7] See, for example, Howard Bowen and Jack Schuster (1986). In addition, in a recent interview on National Public Radio, Leon Lederman, a 1988 physics Nobel laureate, expressed concern over precisely this issue.

[8] Although the SDR is the largest and most comprehensive longitudinal study of scientists in the United States, it could not be used in previous studies of scientific productivity, because it did not contain measures of scientific productivity.

[9] Resource constraints and issues of confidentiality prevented us from studying other subfields or including women in the study.

The empirical analysis focuses on the research productivity of scientists employed full-time at prestigious doctoral-granting departments in their fields, for it is within this sector that the vast majority of research, at least in terms of journal publications, is produced. Thus, it was necessary to make a correction for nonrandom sample selection (James Heckman, 1979; Randall Olsen, 1980). Without this correction, life-cycle aging effects would be biased upward toward zero, since age and ability (which cannot be measured) are likely to be positively correlated in the selected sample, given that elite universities tend to hire relatively many young professors but retain only the best. Before pooling the data from each survey, we correct for this bias by estimating for each of the survey years an ordinary least-squares (OLS) regression predicting the likelihood that a scientist is employed in the selected sector and calculating Olsen's (1980) selectivity-bias correction variable. Included in each regression, among the other variables discussed in Appendix B, are categorical variables to capture the differences in job-market conditions experienced by Ph.D. cohorts.[10]

The model we wish to estimate takes the general form

$$(17)\qquad R_{it} = f(\mathrm{AGE}, V, T, X, S, u)$$

where $R$ is a measure of publishing productivity of scientist $i$ at time $t$, $V$ is vintage, $T$ is the calendar year, $X$ is a vector of other explanatory variables suggested by the conceptual model, $S$ is the sample-selection correction variable, and $u$ is a stochastic error term. The estimation strategy chosen addresses three issues: the identification of aging effects given that age, vintage, and calendar time are nearly perfectly correlated,[11] the presence of a limited dependent variable, and the presence of unmeasurable individual-specific fixed effects.

First, if scientists enter the labor force at the same age (APhD) and work continuously, then the calendar year ($T$) equals age minus APhD plus the year of doctorate, $V$. Because of this linear dependence ($T = \mathrm{AGE} - \mathrm{APhD} + V$), the effects of age, vintage, and calendar time on research productivity cannot be identified separately (William Johnson, 1980). One solution "is to assume non-linearity in the vintage effects" (Johnson, 1980 p. 401). Alternatively, identification is possible if at least one of the three variables "can be eliminated in favor of the underlying theoretical concepts" (Willard Rodgers, 1982 p. 783). Here the two solutions are merged. Following Johnson (1980), Ph.D. cohorts are grouped into intervals represented by categorical variables. The vintage effects are then modeled as a step function with each step corresponding to an interval. Rather than use arbitrary, five-year intervals as does Johnson, however, we used the case studies to identify Ph.D. classes which received a relatively homogeneous knowledge base in graduate school and thus shared a common likelihood of experiencing knowledge-obsolescence when change occurred in their field.[12]

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[10] To make this model tractable (see discussion on multiple criteria for selectivity in G. S. Maddala [1983 pp. 278–83]), we make the following assumptions. First, Ph.D. scientists desire the best academic jobs (see, e.g., R. A. Alpher et al., 1979; Beverly Porter, 1979a, b), and within academia, for the most part, mobility is downwards from the more prestigious to the less prestigious institutions. Thus, to be in the selected sample, individuals must have been chosen by these elite institutions and must have met the unwritten standards for continued employment, standards which are expected to tighten or loosen according to the state of the academic job market. Additional details concerning estimation are presented in Appendix B.

[11] The three effects are not perfectly correlated here, since scientists do not obtain the doctorate and enter the labor force at the same age.

[12] This required ascertaining when major changes in theory or technique occurred in the knowledge base of each subfield. Thus, if the case study for the subfield suggested that a major change occurred in 1949, another in 1955, and the last in 1967, we would group scientists in this field into four intervals and construct corresponding categorical variables: $V_1$ set equal to 1 if the degree was awarded after 1967, 0 otherwise; $V_2$ set equal to 1 if the degree was awarded between 1956 and 1967, 0 otherwise; $V_3$ set equal to 1 if the degree was awarded between 1950 and 1955, 0 otherwise. $V_4$, the excluded (comparison) group would include those scientists educated prior to 1950. In terms of the latest-educated-are-best-educated framework, the step function should rise with each successively later vintage.

A second issue is the presence of a limited dependent variable, since some scientists in the SDR do not publish, or, at least, in certain years do not publish. Consequently, research productivity is truncated at zero, and OLS estimation would result in biased and inconsistent parameter estimates. Thus, we use the maximum-likelihood Tobit (James Tobin, 1958) procedure to estimate the parameters of the research-productivity model.

Finally, individual-specific unmeasurable effects are also an issue. It is well known that some scientists are extremely productive, while others are not. One reason for this is that some scientists possess a particular talent for research, a unique combination of creativity and motivation, which others do not possess (Mary Fox, 1983). Although this special talent may be randomly distributed and uncorrelated with age and vintage in the population of all scientists, this is unlikely in the censored samples considered here.[13] Thus, we chose a fixed-effects estimator, rather than a random-effects (variance-components) estimator, because we expect that the unmeasurable individual-specific effects are correlated with other determinants of publishing productivity, and as a result, the variance-components estimator would be biased and inconsistent (George Judge et al., 1980).

Conceptually, this model can be estimated by including $N-1$ dummies for the individual-specific effects and $T-1$ dummies for the calendar-time effects in a Tobit specification. Inclusion of these fixed effects, however, complicates the analysis in three ways. First is the necessity that there be at least two observations per scientist in order to include the individual-specific dummies.[14] Thus, in assembling the field samples, only those scientists who were in the selected sector more than once were included.[15] We refer to this as sample one in the findings reported below. A second issue that arises in the Tobit specification is that it is not possible to estimate an individual-specific fixed effect for a scientist who never published over the period surveyed. Consequently, a few additional cases were dropped from the analysis, and sample two was formed. (Note, however, that sample two still contains scientists who did not publish in some periods; thus, there remain numerous cases in which the dependent variable is truncated at zero.) Finally, because vintage itself is an individual-specific fixed effect, it proved impossible to obtain an estimate of its effect separate from the other unmeasurable individual-specific fixed effects in the model.[16]

Because of these complications, we chose to estimate two models using Tobit. Model A estimates the life-cycle publishing-productivity relationship for scientists in the elite sector and includes vintage dummy

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[13] For example, this latent, unobservable variable may be correlated with such determinants of publishing productivity as whether the scientist is employed at a Ph.D.-granting institution (i.e., the sample selection variable) or whether the scientist has garnered research support or reputational and positional prestige.

[14] Excluding cases of scientists who were in the selected sector only once raises again the possibility of sample selectivity bias. As discussed in Appendix B, a test of the conjecture that the structure of the publishing-productivity model in each field does not differ for the two groups of scientists, the excluded and included groups, does not lead to a rejection of the null hypothesis.

[15] Note that we do not have a balanced design; scientists may be in the selected sample two, three, or four times. Although an unbalanced design necessitates an adjustment in estimating variance components (Mark Bils, 1985 p. 685), no adjustment is needed in the fixed-effects specification used here.

[16] Heckman and Thomas Macurdy (1980 p. 56) suggest that it would be possible to retrieve separate estimates for the vintage effects indirectly, after controlling for all the individual fixed effects, by regressing the estimated fixed effects obtained in model B on vintage. Our attempt to do so failed, however, because we have too few observations per individual. It also is not possible to obtain separate estimates for the vintage effects directly while controlling for the individual-specific effects in model B by dropping the time-period dummies. Since the vintage of the scientist does not change over time, no vintage estimate can be obtained when individual dummies for the fixed effects are included in the model. Finally, we note that Jerry Hausman and William Taylor (1981) suggest an alternative instrumental-variables technique by which it might be possible to estimate both the time-varying and time-invariant determinants of publishing productivity while controlling for the individual fixed effects. Given the time limitations of our data and our focus on aging, not vintage, we did not use their approach.

variables in addition to the calendar-time dummies and the model's other parameters: age (AGE) and proxies (discussed in Appendix B) for the scientist's research environment (REPRANK), research effort (TEACH/ADMIN), research support (FEDSUP), and previous productivity (SALARY):[17]

$$(18)\quad R_{it} = c_1 + c_2\text{AGE} + c_3\text{REPRANK} + c_4\text{TEACH/ADMIN} + c_5\text{FEDSUP} + c_6\text{SALARY} + c_7 S_{it} + c_8 T_2 + c_9 T_3 + c_{10} T_4 + c_g V_g + e_{it}$$

where $T_2$, $T_3$, and $T_4$ are the calendar-time dummies and $V_g$ $(g = 1,2,\ldots,G)$ are categorical variables from each case study, denoting different vintages of human capital. Since we did not control for the unmeasurable individual-specific fixed effects in this model, the inferences drawn about vintage effects must be viewed with caution. Model A is estimated using both samples one and two. (Because sample two is slightly smaller, in some cases the vintage categories had to be recombined.) The resulting estimates are referred to as A-1 and A-2 below.

Model B provides for a consistent estimate of the pure aging effect by including dummy variables to control for differences in the mean level of publishing productivity attributable to unmeasurables such as talent or motivation.[18] This is done by dropping the vintage variables from model A and including instead the individual-specific dummy variables, $D_{i-1}$, which capture all possible fixed individual-specific effects:[19]

$$(19)\quad R_{it} = c_1 + c_2\text{AGE} + c_3\text{REPRANK} + c_4\text{TEACH/ADMIN} + c_5\text{FEDSUP} + c_6\text{SALARY} + c_7 S_{it} + c_8 T_2 + c_9 T_3 + c_{10} T_4 + c_{i-1} D_{i-1} + e_{it}.$$

By comparing the restricted model A estimated using sample two (A-2) with the less-restricted model B, also estimated using sample two, we can test for the statistical significance of these additional, individual fixed effects and the robustness of the life-cycle effects observed in model A.

## III. Findings

Space precludes the presentation of the econometric findings for all four output measures and for all six subfields. Instead, we illustrate our results focusing only on the parameter estimates for age, vintage, and calendar-time effects for one output measure, PUB1, the two-year count of journal publications.[20] The complete findings for all

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[17] Note that SALARY is, in effect, a lagged variable in the estimating equation, since research productivity is measured beginning one year after the survey date. However, one cannot automatically assume the exogeneity of SALARY. Applying the Hausman (1978) specification test in model A-1, however, we found that the null hypothesis of exogeneity could not be rejected for any output measure in any field. (The quality of graduate training and the age at time of Ph.D. were used as alternative instruments for SALARY.)

[18] Strictly speaking, consistency is a property of large samples and would require a large $T$, which is not possible in most empirical work (Maddala, 1987). If one failed to control for these individual fixed effects, we suspect that the age coefficient in the pooled model would be likely to reflect differences in productivity between older and younger scientists, rather than differences in productivity as the average scientist aged (i.e., the pure aging effect), since the "between" variation in publishing productivity is much larger than the "within" variation.

[19] In estimating model B, care had to be taken to avoid singularities in the data matrix because of the multiple categorical variables representing time period and individual-specific fixed effects. Thus, in some cases, the time-period categories were collapsed, and as a result, the included categorical variables must be interpreted relative to a new omitted category.

[20] These findings control for the likelihood of nonrandom sample selection discussed earlier. Although the sample-selection control variable was not always statistically significant, we found supportive evidence of bias for some form of the model estimated in 24 of the 28 possible combinations of subfields (particle physics was split into two groups; see discussion of findings) and output measures.

TABLE 1—SELECTED REGRESSORS EXPLAINING PUBLICATION COUNTS (PUB1) FOR SUBFIELDS OF PHYSICS

| Subfield and model | AGE | AGE × AGE | $T_2$ | $T_3$ | $T_4$ | $V_1$ / VIN1 | $V_2$ / VIN2 | $V_3$ | $V_4$ | $N$ | log $L$ | LR test $(r, X^2)$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Solid-state physicists: | | | | | | | | | | | | |
| A-1 ($V_1$–$V_4$) | −0.399$^{c}$ | | 2.277$^{c}$ | 2.861$^{c}$ | 4.271$^{c}$ | −5.545 | 6.381$^{a}$ | 7.055$^{b}$ | 7.818$^{c}$ | 182 | −368.444$^{c}$ | |
| | (0.102) | | (0.849) | (0.978) | (1.293) | (4.145) | (3.451) | (3.010) | (2.814) | | | |
| A-2 (VIN1, VIN2) | −0.434$^{c}$ | | 2.014$^{b}$ | 2.632$^{c}$ | 4.172$^{c}$ | −0.962 | 0.224 | | | 159 | −328.904$^{c}$ | |
| | (0.105) | | (0.900) | (0.993) | (1.326) | (1.192) | (1.383) | | | | | |
| B | 2.431$^{c}$ | −0.027$^{c}$ | | −0.091 | −1.822 | | | | | 159 | −237.322$^{c}$ | (51, 174.789)$^{c}$ |
| | (0.735) | (0.009) | | (0.869) | (1.719) | | | | | | | |
| Particle physicists at Ph.D.-granting institutions: | | | | | | | | | | | | |
| A-1 | −0.324$^{c}$ | | 0.934 | 2.515$^{c}$ | −2.878 | −2.687 | −0.574 | 0.214 | | 168 | −306.670$^{c}$ | |
| | (0.091) | | (0.692) | (0.822) | (1.790) | (2.200) | (1.604) | (1.141) | | | | |
| A-2 | −0.291$^{c}$ | | 0.822 | 1.752$^{c}$ | 3.118$^{c}$ | −2.368 | 0.329 | 0.699 | | 149 | −303.371$^{c}$ | |
| | (0.091) | | (0.729) | (0.802) | (1.181) | (2.229) | (1.632) | (1.164) | | | | |
| B | 0.025 | | 0.318 | 1.110 | | | | | | 149 | −229.442$^{c}$ | (51, 97.360)$^{c}$ |
| | (0.279) | | (0.870) | (1.418) | | | | | | | | |
| Particle physicists at FFRDC's: | | | | | | | | | | | | |
| A-1 | −0.499$^{c}$ | | 1.117 | 2.367$^{c}$ | −0.594 | −8.700$^{b}$ | −8.217$^{b}$ | −5.851$^{c}$ | | 157 | −289.160$^{c}$ | |
| | (0.164) | | (1.225) | (1.388) | (2.883) | (4.169) | (3.254) | (2.183) | | | | |
| A-2 | −0.494$^{c}$ | | 0.748 | 2.054 | 0.307 | −9.703$^{b}$ | −9.326$^{c}$ | −4.017$^{a}$ | | 117 | −251.148 | |
| | (0.170) | | (1.239) | (1.354) | (1.715) | (4.173) | (3.316) | (2.265) | | | | |
| B | −0.839$^{c}$ | | | 2.421$^{b}$ | 3.337$^{a}$ | | | | | 117 | −174.891$^{c}$ | (39, 152.514)$^{c}$ |
| | (0.334) | | | (1.096) | (1.879) | | | | | | | |
| Atomic and molecular physicists: | | | | | | | | | | | | |
| A-1 | −0.164$^{a}$ | | 1.249 | 2.127 | 4.188$^{b}$ | 1.264 | | | | 89 | −172.207$^{c}$ | |
| | (0.117) | | (1.460) | (1.501) | (1.875) | (1.965) | | | | | | |
| A-2 | −0.060 | | 1.069 | 1.290 | 2.735 | 1.661 | | | | 77 | −163.590$^{c}$ | |
| | (0.131) | | (1.493) | (1.520) | (1.905) | (1.953) | | | | | | |
| B | 1.339$^{a}$ | −0.017$^{a}$ | | −0.251 | 0.050 | | | | | 77 | −114.889$^{c}$ | (22, 95.358)$^{c}$ |
| | (0.906) | (0.011) | | (1.283) | (2.067) | | | | | | | |

*Notes:* Variable definitions and descriptive statistics are found in Appendix B (Table B1). The likelihood-ratio test (LR test) reports the number of restrictions ($r$) and the chi-square statistic for the comparison of models A-2 and B. All tests of significance are one-tailed, with the exception of time period and vintage effects. Standard errors are in parentheses.

[a] Statistical significance at 0.10; [b] at 0.05; [c] at 0.01.

TABLE 2—SELECTED REGRESSORS EXPLAINING PUBLICATION COUNTS (PUB1) FOR SUBFIELDS OF EARTH SCIENCE

| Subfield and model | AGE | AGE × AGE | $T_2$ | $T_3$ | $T_4$ | $V_1$ / VIN1 | $V_2$ / VIN2 | $V_3$ / VIN3 | $V_4$ | $V_5$ | $N$ | log $L$ | LR test $(r, X^2)$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Oceanographers: | | | | | | | | | | | | | |
| A-1 ($V_1$, $V_2$) | −0.067$^{a}$ | | −1.270 | −0.074 | −0.687 | −3.125$^{c}$ | −2.310$^{b}$ | | | | 57 | −83.466 | |
| | (0.049) | | (1.181) | (0.784) | (0.892) | (1.181) | (1.005) | | | | | | |
| A-2 (VIN1) | −0.002 | | −0.860 | 0.085 | −1.155 | 0.185 | | | | | 51 | −73.492 | |
| | (0.054) | | (0.881) | (0.835) | (0.902) | (0.728) | | | | | | | |
| B | 0.928$^{b}$ | −0.020$^{c}$ | | 2.808$^{c}$ | 3.194$^{b}$ | | | | | | 51 | −48.945$^{c}$ | (11, 40.251)$^{c}$ |
| | (0.553) | (0.008) | | (0.910) | (1.441) | | | | | | | | |
| Geophysicists: | | | | | | | | | | | | | |
| A-1 ($V_1$–$V_4$) | −0.461$^{c}$ | | 4.287$^{c}$ | 3.158$^{b}$ | 4.487$^{c}$ | −5.393 | −2.425 | −2.223 | −2.146 | | 78 | −151.629$^{c}$ | |
| | (0.128) | | (1.382) | (1.472) | (1.582) | (4.475) | (3.637) | (2.764) | (2.828) | | | | |
| A-2 (VIN1–VIN3) | −0.322$^{c}$ | | 4.171$^{c}$ | 2.954$^{b}$ | 4.134 | −2.049 | 0.069 | −0.325 | | | 69 | −146.077$^{c}$ | |
| | (0.120) | | (1.335) | (1.424) | (1.538) | (3.659) | (2.803) | (2.008) | | | | | |
| B | 2.370$^{c}$ | −0.020$^{b}$ | | −2.139$^{b}$ | −2.644 | | | | | | 69 | −95.747$^{c}$ | (18, 98.097)$^{c}$ |
| | (0.779) | (0.009) | | (1.052) | (1.660) | | | | | | | | |
| Geologists: | | | | | | | | | | | | | |
| A-1 | −0.081 | | −0.874 | 0.494 | 0.524 | 2.013 | 2.675 | 1.527 | 1.816 | 1.702 | 172 | −231.664$^{c}$ | |
| | (0.075) | | (0.654) | (0.691) | (0.820) | (2.705) | (2.396) | (2.025) | (1.801) | (1.349) | | | |
| A-2 | 0.097 | | −1.063 | −0.281 | −0.650 | 6.224$^{b}$ | 6.136$^{b}$ | 4.389$^{a}$ | 3.966$^{a}$ | 2.700$^{a}$ | 130 | −204.921$^{b}$ | |
| | (0.097) | | (0.682) | (0.739) | (0.896) | (3.129) | (2.820) | (2.329) | (2.025) | (1.431) | | | |
| B | −0.383$^{a}$ | | | 1.651$^{a}$ | 1.902 | | | | | | 130 | −172.085$^{c}$ | (33, 65.671)$^{c}$ |
| | (0.267) | | | (0.969) | (1.460) | | | | | | | | |

*Notes:* Variable definitions and descriptive statistics are found in Appendix B (Table B2). The likelihood-ratio test (LR test) reports the number of restrictions ($r$) and the chi-square statistic for the comparison of models A-2 and B. All tests of significance are one-tailed, with the exception of time period and vintage effects. Standard errors are in parentheses.

[a] Statistical significance at 0.10; [b] at 0.05; [c] at 0.01.

output measures are available upon request. Although the general conclusions are not particularly sensitive to the output measure used, differences for the other output measures are noted. Table 1 summarizes the findings for the physics areas investigated, and Table 2 summarizes the earth science results. Appendix B and Tables B1 and B2 describe the variables and report descriptive statistics for each of the fields.[21]

### A. *Physics*

Three areas in physics are investigated: solid-state/condensed-matter physics, particle physics, and atomic and molecular physics. In layman's terms, solid-state/condensed-matter physics studies why substances have certain electrical properties, as well as other properties such as color and translucence. It is the largest subfield in physics, and research in this area is responsible for the transistor and superconductors, two of the most commercially viable developments in physics. Elementary particle physics focuses on the smallest bits of matter that are known to exist. Research in elementary particle physics looks for the laws governing the four fundamental interactions—nuclear (strong), electromagnetic, weak, and gravitational—with the final aim of unifying these interactions by finding some common origin. Abstract theorists working on unification are often depicted as involved in a "religious quest," handed them by Einstein, or, as is commonly stated in the literature, the "search for the Holy Grail." The fundamental equations which concern atomic and molecular physicists come from quantum mechanics. As a result, the equations have been known for approximately 60 years, although the solutions remain elusive. Theoretical atomic physicists continue to seek solutions to these equations.

*Solid-State / Condensed-Matter Physics.* Overall, the results are strong. The null hypothesis that the parameters of the model are jointly zero can be rejected at a confidence level exceeding 0.99. The coefficients on the time variables in A-1 and A-2 indicate that output has increased in each successive time period (by about 2–4 articles) compared to the earliest period, 1973. More-recent vintages are more productive (by about 6–8 articles) than the earliest vintage (the omitted category), those educated prior to 1948, although the difference is only statistically significant for all measures of output for $V_3$ and $V_4$. This is consistent with the case study's conjecture that the introduction of new experimental techniques as well as many-body theory and renormalization may have had the effect of depressing the output of the pre-1948 vintage. There is, however, little indication that publishing productivity varies significantly among later vintages. Not surprisingly, when the vintages are compressed into just three categories in A-2, there is no statistical evidence of vintage effects. The results also suggest the presence of other individual fixed effects in addition to the specified vintage effects. The likelihood-ratio test comparing model A-2 and model B indicates that the null hypothesis that there are no individual-specific unmeasurable fixed effects, after controlling for vintage, can be rejected at a level of significance exceeding 0.01.

Of particular interest to this study is the coefficient on aging. In A-1 and A-2, there is strong evidence of life-cycle effects, a decline of 0.4 articles per period. When the fixed-effects model is estimated (model B), the life-cycle effects persist. The coefficients on age and age-squared suggest a nonlinear aging effect, with publishing productivity reaching a peak at age 45. (For PUB2, the peak comes at 41, for PUB3 at 45, and for PUB4 at 40.)

*Particle Physics.* The prestigious sector in this area consists of scientists employed both at Ph.D.-granting institutions and at federally funded research and development centers (FFRDC's). These two groups are studied separately, since their research environments differ considerably.[22]

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[21] A full description of the subfield samples and descriptive statistics for the other explanatory variables are available upon request.

[22] We did not consider and, in fact, had no way of modeling the possibility of endogenous sector choice in

(*i*) *Particle physicists at Ph.D.-granting institutions*. The overall results are strong and statistically significant. Again the null hypothesis that parameters of the model are jointly zero can be rejected. A-1 shows that productivity is significantly higher, by about 2.5 articles, in 1977 ($T_3$). The parameter estimates for the vintage variables imply that, compared to the group educated when field theory was in its prime (represented by the excluded vintage dummy), later vintages are less productive. This is consistent with evidence presented in the case study that those educated when field theory was important may have enjoyed an edge in particle physics. The differences, however, are only statistically significant for output measures PUB2 and PUB4, and then only between the field-theory group and the latest vintage ($V_1$), those receiving doctorates since 1970.

When individual fixed effects are not controlled for (model A), there is evidence of aging effects, a decline of 0.3 articles per period, much smaller, however, than was observed in solid-state physics. Model B shows that the null hypothesis that the unmeasurable individual fixed effects are jointly zero must be rejected. Moreover, once these effects are controlled for, there is no evidence to support the hypothesis that research activity declines over the life cycle. This outcome is not totally unexpected. The conceptual model implies that, when satisfaction from research is an argument in the utility function, research activity remains positive until retirement. In addition, the model suggests that the productivity profile is likely to be flatter when greater satisfaction is derived from puzzle-solving activity. Among the six groups studied, theoretical particle physicists most clearly fit this picture.

(*ii*) *Particle physicists at* FFRDC's. The results are fairly strong, although the null hypothesis that the parameters of the model are jointly zero cannot be rejected in model A-2. As A-1 indicates, only in 1975 is there statistical support for the presence of time-period effects. Both estimations of model A, however, suggest that FFRDC particle physicists educated after 1957 are less productive than those educated before (about 4–10 articles less) and that the group educated after 1963 ($V_1$ and $V_2$) may be less productive than those educated between 1957 and 1963 ($V_3$). This is consistent with the case study's finding that the field-theory generation and those educated while field theory was still in vogue may have enjoyed an edge in particle physics.

As in the case of solid-state physics, there is evidence of a strong aging effect, a decline of 0.5 articles per period. Even after controlling for all individual-specific effects, research activity declines significantly with age. Apparently, particle physicists located at FFRDC's focus more heavily on the investment component of research than their peers at Ph.D.-granting institutions. One explanation for this is that more phenomenologists and experimentalists and fewer pure theorists are located at FFRDC's.

*Atomic and Molecular Physics*. Again the results are strong, although there is scant evidence of time-period effects. Output is significantly higher than the base period only for 1979 ($T_4$) for PUB1 and PUB3. Although the more-recent vintage is more productive than the earlier vintage, the difference is not statistically significant. This is consistent with the case study's observation that no major revolution has occurred since these scientists received their doctorates.

A statistically significant inverse relationship between age and publishing productivity is observed in A-1, (for PUB3, as well), although the confidence level is less than 0.95. This statistically significant age effect, however, does not hold up when the smaller data set of sample two is used to estimate model A. Just as in the previous fields, the null hypothesis of the absence of unmeasurable individual fixed effects is rejected. Controlling for these effects, however, as model B indicates, confirms the previous finding that productivity declines with age. (This is

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particle physics. Our reading of the literature, however, and our correspondence and discussions with physicists do not lead us to believe that the choice of sector is endogenous to the model of publishing productivity in this case.

also true for PUB3). It appears (although only at a 0.90 confidence level) that output at first increases and then diminishes as the scientist ages, reaching a peak at age 39. (The peak for PUB3 is age 40).

### B. *Earth Science*

The three areas studied are oceanography, geophysics, and geology. Oceanography relies heavily on geophysical theory and methods to investigate the oceans and lands beneath them; geophysics is the study of the earth, using the basic principles of physics; and geology focuses on how the earth was formed, its composition, history, and changes. In this study, geology includes the specialties of mineralogy, petrology, stratigraphy, sedimentation, paleontology, structural geology (tectonics), and geomorphology.

If there is one development over the past 50 years in earth science that has had the stature of a major conceptual change, it is clearly the revolutionary theory of a dynamic earth, called plate tectonics, developed in the mid-to-late 1960's. Doubt exists, however, as to whether the new plate-tectonic generation of scientists possesses a knowledge edge compared to their predecessors, particularly in geology and perhaps to a lesser extent in oceanography, where research activity often focuses on observation and classification, two activities which are thought to be unaffected by a major conceptual change.

*Oceanography*. The results are generally weak, and to some extent, this is undoubtably attributable to the small sample size. The null hypothesis that the parameters of the model are jointly zero can only be rejected in model B. Time-period effects are not evident in model A, although they are present when output is adjusted for quality in PUB3 and PUB4. Compared to the earliest vintage (those receiving degrees prior to 1965), each later vintage in A-1 is, on average, less productive. (The null hypothesis of no difference must be accepted, however, when output is adjusted for coauthorship, PUB2.) Thus, it does not appear that those educated subsequent to the plate-tectonic revolution gained a knowledge edge. The results also are not consistent with an alternative hypothesis, offered by one earth scientist, that those most likely caught up in the revolution would tend to be the most productive. The productivity differences between vintages, however, disappear when the vintage categories are compressed in A-2.

In A-1, publishing productivity is found to decline significantly with age; however, it declines by less than 0.1 article per period. (When the output measure is PUB3, the age variable is not statistically significant.) After controlling for all individual-specific fixed effects in model B, statistically significant life-cycle effects are also present. Output at first rises with age and then declines, and this decline begins very early in the career. (This is also true for PUB2, but productivity appears to decline linearly with age for PUB3 and PUB4).

*Geophysics*. The overall results for this field are strong. In all cases, the null hypothesis that the parameters of this model are jointly zero can be rejected at confidence levels exceeding 0.99. As model A shows, there are statistically significant positive differences (of 3–4 articles) in mean publishing rates in each time period compared to the base period, 1973. With one exception, all vintage effects are negative when compared to the earliest vintage, but only for the most recent vintage in the model for PUB4 is the difference statistically significant. These results do not support the latest-are-best-educated model of knowledge obsolescence. If anything, they suggest that the plate-tectonic generation has failed to keep pace with its predecessors.

Once again, there is evidence of an inverse relationship between publishing productivity and age (a decline of about 0.5 articles per period in A-1), and the results do not change appreciably in A-2. Furthermore, these life-cycle effects persist in model B. Output peaks quite late in the career, at age 59, and then declines. (The peak is 55 for PUB2, 58 for PUB3, and 53 for PUB4).

*Geology*. The empirical results are again generally strong in terms of the overall significance of the models. There does not, however, appear to be a systematic pattern of differences over time in the mean level of publishing productivity, and, although the later vintages appear to be more productive than the earliest vintage, the differences are statistically significant only in A-2. This is not surprising. Geology is largely an observational field where vintage may be of little importance. As one author suggests (John Law, 1980 p. 160), "there is something about subjects such as geology which permits a conceptual pluralism that is relatively rare in physics or chemistry." Thus, even in the face of major revolutions in thought and practice, research may proceed in the usual manner.

Model A does not indicate the presence of aging effects. After controlling for all individual fixed effects in model B, however, aging effects do appear (a decline of 0.4 articles per period), although the coefficient is only significant at the 10-percent level.

## IV. Conclusions

The major finding of this study is that, with the exception of particle physicists employed in Ph.D.-granting departments, life-cycle effects are present in a fully specified model of publishing productivity which, among other things, controls for individual fixed effects such as motivation and ability. Stated differently, there is evidence that, on average, scientists become less productive as they age. The aging effect that is found is attributed to age per se and not to the possibility that, for some reason, older scientists in the sample have different attributes, values, or access to resources than younger members of the sample. Hence, research activity over the life cycle appears to be investment-motivated.

The results, although tentative, also suggest that, for the most part, vintage matters, but not in the way predicted from a latest-educated-are-best-educated point of view. With the possible exception of geology, more recent vintages are never found to be significantly more productive than earlier vintages. Perhaps, in retrospect, this outcome is not all that surprising, given that the case studies suggest that, in at least some of the fields, more-recent vintages may not have had a knowledge edge. For example, the physics case study suggests that atomic and molecular physics has not experienced dramatic changes in thought or technique during the past 40 years since the upheaval brought about by the quantum revolution. In other fields, such as solid-state/condensed-matter physics, although numerous developments could have produced vintage effects, it appears that there is a role for what one physicist called "ditch diggers," scientists who remain active by producing "backwater" research. Furthermore, the case study also suggests that, in particle physics, some later vintages may have enjoyed less of a knowledge edge because they were trained in concepts that subsequently proved to be dead ends. In addition, the earth-science case study raises doubt as to whether the plate-tectonic revolution as well as advances in computer technology would render older scientists coming from earlier vintages less productive.

There is, however, another more speculative explanation as to why the latest vintages, with the possible exception of geology, proved to be no more productive than the earlier vintages. During the 1960's and very early 1970's science grew very rapidly. It is possible that scientists obtaining doctorates during this period of rapid expansion may have been, on average, not as talented or motivated as scientists coming from earlier cohorts, which represent a smaller, more elite portion of the population. As a result, even if these scientists have a knowledge edge, a "talent deficit" may make them no more productive than their peers.

In the econometric model specified, a sample-selection variable was introduced to control for market conditions affecting employment location, and vintage dummies were introduced to capture knowledge-obsolescence effects. Since no variable directly controlled for the average ability or motivation of the cohort, it is possible that the vintage dummies reflect not only change in knowledge but also change in the average ability or motivation of the cohort. This would explain why the most-recent vintages are never found to be more productive, with the possible exception of geology. The results also suggest that this ability/motivation argument might be extended well into the 1970's and 1980's, long after the growth in science peaked, perhaps because the best students were attracted into careers in law, business, and medicine. Bowen and Schuster (1986 pp. 224–6) document a marked shift away from the academic sector in the career choices of such highly talented members of the population as Rhodes scholars and Phi Beta Kappa members over the period 1965–1979.

Together, the aging and vintage results suggest that, during the next 10 or 15 years, the American scientific community will not be as productive as it was in the 1960's and early 1970's, assuming market conditions do not change dramatically. Not only will the community be older, but over time the community will become increasingly dominated by scientists who did not come from particularly productive cohorts.

## APPENDIX A—DATA

Previous research on the relationship between age and scientific performance has been hampered by the lack of a comprehensive data base containing measures of productivity for scientists. We have assembled such a data base by using a computer algorithm to link the journal-publication data contained in the *Science Citation Index* (SCI) with the biennial *Survey of Doctorate Recipients* (SDR).

The number of journal articles is chosen as the measure of productivity, since it is generally recognized that the journal literature is the major outlet for recording scientific advances in many disciplines (Henry Menard, 1971). Publication counts are established for scientists trained, as designated in either the SDR or the *Survey of Earned Doctorates* as biochemists, earth scientists, physicists (excluding astronomers and astrophysicists), or physiologists by a computer algorithm using the source and corporate address files of the SCI. We count the flow of publications for a period of two years, beginning one year after the survey date of the scientist (1973, 1975, 1977, or 1979), given evidence on the length of the lag between the inception of the research project and the time at which the resulting output is likely to appear (Nelson and Pollock, 1970).

The magnitude of this project can be seen by considering the size of the two files that were linked. On the SDR side, even though we restricted the analysis to scientists in just four fields, including all sectors of employment there were 18,909 records for the 1973–1979 interview period. On the SCI side, over the period 1974–1981, there were in excess of 9.6 million entries in the *Source Index*. Because of the confidential nature of the SDR, all work linking the data bases was performed by the Data Processing Unit at the *National Research Council* (NRC). The initial match procedure used was a variant of that developed by George Boyce at NRC for the study conducted by Lyle Jones et al. (1982). The match queued on last name, first name, middle initial (if present), state/country, and zip code. The completed match is approximately 95 percent accurate (Stephan and Levin, 1988).

A large part of this research involved the development of case studies to specify the market-determined dummy variables for cohort effects used in the selection equation, as well as the vintage dummy variables included in model A. These case studies are available upon request. Information for the case studies was gathered from various publications, including those produced by outside observers of the field such as historians and sociologists of science, personal interviews, and a mail survey. In interviews and in the questionnaire, scientists were asked to identify changes occurring in their specialty, either in theory or in research techniques, that could have negative effects on the productivity of persons trained before the innovation occurred. Two physicists, Steve Manson and Steve Sigur from Atlanta, gave particularly freely of their time, as did Spencer Weart of the American Institute of Physics (AIP). In addition, Beverly Porter of AIP was extremely helpful in identifying cohort effects. In physics, the survey was sent to 63 scientists, many of whom were members of the Brinkman Panels, established by NRC to review the state of physics in the 1980's. Of the 63, 26 physicists replied, either by completing the survey or by writing a letter. Of the 38 surveys mailed to geoscientists, eight returns were particularly useful. The late Bill Menard, a distinguished oceanographer, and William Glen, editor of *Eos*, were especially helpful.

## APPENDIX B—ESTIMATION

The Olsen technique was used to obtain the sample-selection correction variable, SVAR. For each survey year, the probability of sample inclusion in a Ph.D.-granting department was estimated by ordinary least squares using the following regressors: the quality of graduate training, age, age-squared, whether the respondent was born in the South, whether the respondent was born in the non-South or Canada, the age at time of Ph.D., market-determined cohort effects (dummy variables), and interactions between the quality of graduate training and the market cohort effects. All of these variables, with the exception of categorical variables representing the quality of graduate training and dummy variables for the cohort effects are taken from the National Research Council's *Survey of Doctorate Recipients* (SDR). Data on the rankings of graduate departments over time (Hayward Keniston, 1959; Allan Cartter 1966; Kenneth Roose and Charles Anderson, 1970; Jones et al., 1982) are used to sort the Ph.D.-granting institutions into five categories, ranging from departments that were not ranked to departments

TABLE B1—DESCRIPTIVE STATISTICS FOR SUBFIELDS OF PHYSICS

| Variable | Mean | SD | $N$ |
|---|---|---|---|
| Solid-state physicists: | | | |
| PUB1 = total count of publications for two-year period | 3.830 | 4.086 | 182 |
| AGE = age | 41.533 | 7.093 | 182 |
| $T_1 = 1$ if year of survey $= 1973$; 0 otherwise | 0.280 | 0.450 | 182 |
| $T_2 = 1$ if year of survey $= 1975$; 0 otherwise | 0.335 | 0.473 | 182 |
| $T_3 = 1$ if year of survey $= 1977$; 0 otherwise | 0.269 | 0.445 | 182 |
| $T_4 = 1$ if year of survey $= 1979$; 0 otherwise | 0.115 | 0.320 | 182 |
| $V_1 = 1$ if year of Ph.D. $> 1972$; 0 otherwise | 0.033 | 0.179 | 182 |
| $V_2 = 1$ if $1963 \leq$ year of Ph.D. $\leq 1972$; 0 otherwise | 0.473 | 0.501 | 182 |
| $V_3 = 1$ if $1956 \leq$ year of Ph.D. $\leq 1962$; 0 otherwise | 0.357 | 0.480 | 182 |
| $V_4 = 1$ if $1948 \leq$ year of Ph.D. $\leq 1955$; 0 otherwise | 0.099 | 0.299 | 182 |
| $V_5 = 1$ if year of Ph.D. $< 1948$; 0 otherwise | 0.039 | 0.193 | 182 |
| VIN1 = 1 if year of Ph.D. $> 1963$; 0 otherwise | 0.516 | 0.501 | 159 |
| VIN2 = 1 if $1956 \leq$ year of Ph.D. $\leq 1962$; 0 otherwise | 0.365 | 0.483 | 159 |
| VIN3 = 1 if year of Ph.D. $< 1956$; 0 otherwise | 0.119 | 0.325 | 159 |
| Particle physicists at Ph.D.-granting institutions: | | | |
| PUB1 = total count of publications for two-year period | 2.982 | 2.903 | 168 |
| AGE = age | 39.786 | 6.841 | 168 |
| $T_1 = 1$ if year of survey $= 1973$; 0 otherwise | 0.280 | 0.450 | 168 |
| $T_2 = 1$ if year of survey $= 1975$; 0 otherwise | 0.333 | 0.473 | 168 |
| $T_3 = 1$ if year of survey $= 1977$; 0 otherwise | 0.286 | 0.453 | 168 |
| $T_4 = 1$ if year of survey $= 1979$; 0 otherwise | 0.101 | 0.303 | 168 |
| $V_1 = 1$ if year of Ph.D. $> 1970$; 0 otherwise | 0.143 | 0.351 | 168 |
| $V_2 = 1$ if $1964 \leq$ year of Ph.D. $\leq 1970$; 0 otherwise | 0.387 | 0.489 | 168 |
| $V_3 = 1$ if $1957 \leq$ year of Ph.D. $\leq 1963$; 0 otherwise | 0.333 | 0.473 | 168 |
| $V_4 = 1$ if year of Ph.D. $< 1957$; 0 otherwise | 0.137 | 0.345 | 168 |
| Particle physicists at FFRDC's: | | | |
| PUB1 = total count of publications for two-year period | 2.682 | 3.843 | 157 |
| AGE = age | 39.433 | 6.841 | 157 |
| $T_1 = 1$ if year of survey $= 1973$; 0 otherwise | 0.248 | 0.434 | 157 |
| $T_2 = 1$ if year of survey $= 1975$; 0 otherwise | 0.299 | 0.459 | 157 |
| $T_3 = 1$ if year of survey $= 1977$; 0 otherwise | 0.312 | 0.465 | 157 |
| $T_4 = 1$ if year of survey $= 1979$; 0 otherwise | 0.140 | 0.348 | 157 |
| $V_1 = 1$ if year of Ph.D. $> 1970$; 0 otherwise | 0.172 | 0.379 | 157 |
| $V_2 = 1$ if $1964 \leq$ year of Ph.D. $\leq 1970$; 0 otherwise | 0.440 | 0.498 | 157 |
| $V_3 = 1$ if $1957 \leq$ year of Ph.D. $\leq 1963$; 0 otherwise | 0.299 | 0.459 | 157 |
| $V_4 = 1$ if year of Ph.D. $< 1957$; 0 otherwise | 0.089 | 0.286 | 157 |
| Atomic and molecular physicists: | | | |
| PUB1 = total count of publications for two-year period | 3.258 | 4.368 | 89 |
| AGE = age | 44.371 | 9.048 | 89 |
| $T_1 = 1$ if year of survey $= 1973$; 0 otherwise | 0.258 | 0.440 | 89 |
| $T_2 = 1$ if year of survey $= 1975$; 0 otherwise | 0.303 | 0.462 | 89 |
| $T_3 = 1$ if year of survey $= 1977$; 0 otherwise | 0.281 | 0.452 | 89 |
| $T_4 = 1$ if year of survey $= 1979$; 0 otherwise | 0.157 | 0.366 | 89 |
| $V_1 = 1$ if year of Ph.D. $> 1963$; 0 otherwise | 0.416 | 0.496 | 89 |
| $V_2 = 1$ if year of Ph.D. $\leq 1963$; 0 otherwise | 0.584 | 0.496 | 89 |

that were in the top five. These intermediate results are available upon request.

Our commitment to a fixed-effects specification necessitated restricting the analysis to scientists employed in the top sector more than once. This meant excluding approximately 17 percent of the observations. The predominant reason that scientists appeared in the top sector only once was because they were surveyed (or responded) only once. To investigate the possibility that other scientists systematically self-selected out of the top sector, following Daniel Hamermesh (1987), we tested whether the structure of model A differed between those who were in the top sector only once and those who were in more than once. On the basis of likelihood-ratio tests, the null hypothesis of no difference in the basic structure of model A for the two groups could not be rejected at the 95-percent level for all measures of output in all subfields.

TABLE B2—DESCRIPTIVE STATISTICS FOR SUBFIELDS OF EARTH SCIENCE

| Variable | Mean | SD | $N$ |
|---|---|---|---|
| Oceanographers: | | | |
| PUB1 = total count of publications for two-year period | 2.105 | 1.839 | 57 |
| AGE = age | 40.333 | 7.666 | 57 |
| $T_1 = 1$ if year of survey = 1973; 0 otherwise | 0.211 | 0.411 | 57 |
| $T_2 = 1$ if year of survey = 1975; 0 otherwise | 0.281 | 0.453 | 57 |
| $T_3 = 1$ if year of survey = 1977; 0 otherwise | 0.281 | 0.453 | 57 |
| $T_4 = 1$ if year of survey = 1979; 0 otherwise | 0.228 | 0.423 | 57 |
| $V_1 = 1$ if year of Ph.D. > 1969; 0 otherwise | 0.298 | 0.462 | 57 |
| $V_2 = 1$ if $1965 \leq$ year of Ph.D. $\leq 1969$; 0 otherwise | 0.579 | 0.498 | 57 |
| $V_3 = 1$ if year of Ph.D. < 1965; 0 otherwise | 0.123 | 0.331 | 57 |
| VIN1 = 1 if year of Ph.D. > 1969; 0 otherwise | 0.275 | 0.451 | 51 |
| VIN2 = 1 if year of Ph.D. $\leq 1969$; 0 otherwise | 0.725 | 0.451 | 51 |
| Geophysicists: | | | |
| PUB1 = total count of publications for two-year period | 3.654 | 4.404 | 78 |
| AGE = age | 41.474 | 8.208 | 78 |
| $T_1 = 1$ if year of survey = 1973; 0 otherwise | 0.218 | 0.416 | 78 |
| $T_2 = 1$ if year of survey = 1975; 0 otherwise | 0.282 | 0.453 | 78 |
| $T_3 = 1$ if year of survey = 1977; 0 otherwise | 0.282 | 0.453 | 78 |
| $T_4 = 1$ if year of survey = 1979; 0 otherwise | 0.218 | 0.416 | 78 |
| $V_1 = 1$ if year of Ph.D. > 1969; 0 otherwise | 0.321 | 0.470 | 78 |
| $V_2 = 1$ if $1965 \leq$ year of Ph.D. $\leq 1969$; 0 otherwise | 0.180 | 0.386 | 78 |
| $V_3 = 1$ if $1960 \leq$ year of Ph.D. $\leq 1964$; 0 otherwise | 0.282 | 0.453 | 78 |
| $V_4 = 1$ if $1955 \leq$ year of Ph.D. $\leq 1959$; 0 otherwise | 0.115 | 0.322 | 78 |
| $V_5 = 1$ if year of Ph.D. < 1955; 0 otherwise | 0.103 | 0.305 | 78 |
| VIN1 = 1 if year of Ph.D. > 1969; 0 otherwise | 0.333 | 0.475 | 69 |
| VIN2 = 1 if $1965 \leq$ year of Ph.D. $\leq 1969$; 0 otherwise | 0.203 | 0.405 | 69 |
| VIN3 = 1 if $1960 \leq$ year of Ph.D. $\leq 1964$; 0 otherwise | 0.290 | 0.457 | 69 |
| VIN4 = 1 if year of Ph.D. < 1960; 0 otherwise | 0.058 | 0.235 | 69 |
| Geologists: | | | |
| PUB1 = total count of publications for two-year period | 1.535 | 2.087 | 172 |
| AGE = age | 47.500 | 10.245 | 172 |
| $T_1 = 1$ if year of survey = 1973; 0 otherwise | 0.273 | 0.447 | 172 |
| $T_2 = 1$ if year of survey = 1975; 0 otherwise | 0.291 | 0.455 | 172 |
| $T_3 = 1$ if year of survey = 1977; 0 otherwise | 0.244 | 0.431 | 172 |
| $T_4 = 1$ if year of survey = 1979; 0 otherwise | 0.192 | 0.395 | 172 |
| $V_1 = 1$ if year of Ph.D. > 1970; 0 otherwise | 0.134 | 0.341 | 172 |
| $V_2 = 1$ if $1965 \leq$ year of Ph.D. $\leq 1969$; 0 otherwise | 0.081 | 0.274 | 172 |
| $V_3 = 1$ if $1960 \leq$ year of Ph.D. $\leq 1964$; 0 otherwise | 0.244 | 0.431 | 172 |
| $V_4 = 1$ if $1955 \leq$ year of Ph.D. $\leq 1959$; 0 otherwise | 0.204 | 0.404 | 172 |
| $V_5 = 1$ if $1945 \leq$ year of Ph.D. $\leq 1954$; 0 otherwise | 0.192 | 0.395 | 172 |
| $V_6 = 1$ if year of Ph.D. < 1945; 0 otherwise | 0.145 | 0.354 | 172 |

In addition to age, vintage, the correction for sample-selectivity bias (SVAR), and time-period dummy variables, model A also controls for REPRANK, SALARY, ADMIN/TEACH, and FEDSUP. REPRANK is taken from Jones et al. (1982), while the other variables are derived from data in the SDR. REPRANK measures the reputational rating of graduate departments and is included given the abundance of evidence that productivity is positively related to department quality (Long, 1978; Long and McGinnis, 1981; Fox, 1983). Moreover, it is also highly correlated with other measures of the richness of the research environment in which the scientist works. SALARY, the scientist's adjusted (for inflation) annual salary, is related to the scientist's past productivity and hence serves as a proxy for reputational prestige and cumulative advantage. ADMIN/TEACH captures whether the scientist devotes considerable effort to nonresearch activities. Finally, FEDSUP indicates whether the scientist presently has government research support. Although not reported in the text, the findings with respect to all control variables were generally consistent with expectations.

The preliminary analysis also considered additional explanatory variables. These included such proxies for ability as whether the individual attended a select undergraduate institution, the rating of the graduate institution attended, and proxies (dummy variables) to capture exogenous differences in publishing productivity by field because scientists may be working in fields other than their field of training. Since in no case did it appear that these additional regressors had a marked effect on the results, they have been omitted from the findings reported here. Also considered in preliminary work was a dummy variable for tenure status and a variable for the number of years since tenure was received. Unfortunately, because there were so many cases in which the scientist failed to indicate tenure status and numerous inconsistencies between the years since tenure and the reported employment history, analysis including these variables was not pursued further.

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