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Management of Science, Serendipity, and Research Performance: Evidence from Scientists' Survey

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Key words: science, serendipity, productivity, research management

Abstract

This study investigates the impact of management style on research performance in science. If a managerial role is played by a leading scientist in the research team, that is considered management-research integration. If not, we consider that management and research are separated. We found that separating the managerial and research role has a positive effect on the number of papers published for that research project. In contrast, management-research integration is positively associated with the quality of the paper through allowing researchers to pursue serendipitous findings. These results show the trade-off between research efficiency and quality in science via who plays the managerial role and the leading research role.

1 Introduction

Would Alexander Fleming have discovered penicillin if he had been part of a large research team? Would he have changed his research plan on influenza to explore a culture contaminated with a fungus in 1928 if his research project had been managed by an efficient project manager?

Using the scientists' survey in the U.S. and Japan, this paper explores management-research separation and its effect on serendipity and productivity in science. Serendipity plays an important role in science. Alexander Fleming's discoveries of the enzyme lysozyme in 1923 and penicillin from the mould Penicillium notaum in 1928 are frequently cited examples of serendipity. The cosmic background radiation identified by Bell Lab scientists Arno Penzias and Robert Wilson, the circular structure of benzene discovered by Friedrich Kekulé, X-rays developed by Antoine Henri Becquerel, and Hans Christian Ørsted's finding that electric currents create magnetic fields are also well-quoted examples of serendipity. Many major discoveries have been made by people who were looking for

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something very different. As will be discussed in the next section, serendipity seemingly happens in a random manner, implying that serendipity is not manageable. However, one of the objectives of this paper is to explore how serendipity can be managed in a research organization.

The pattern of scientific research, often called “Big Science,”[1] has changed since World War II. Research projects have become increasingly larger in scope and size. The number of researchers on a research project has increased as well (Adams et al. 2005). Advanced research instruments require large budgets and a wide range of specific expertise. Thus, large-scale, inter-disciplinary, and inter-organizational research has been of significance (Agrawal and Goldfarb 2008, Austin et al. 2012). The importance of priority in scientific discovery has also increased (Ellison 2002, Stephan and Levin 1992). Since research is increasingly accomplished in teams across nearly all fields (Wuchty et al. 2007), management of the research team becomes significant to research performance in science.

Exploring the scientists’ survey, this paper investigates three points. The first point examines whether serendipity has a positive effect on the quality of research. Much of the anecdotal evidence suggests that serendipity does indeed have a positive effect on the quality of research. However, this point, which is reviewed in the next section, has not been empirically examined.

The second point considers the effect of research management on serendipity. When a scientist makes a serendipitous finding, he or she is faced with an important choice: to flexibly change the research plan to pursue the serendipitous events or to stick closely to the initial plan. The serendipitous finding comes unexpectedly in the form of a very crude and nascent condition. Thus, the scientist is forced to make an intuitive decision to pursue or not to pursue. As is reviewed in the following section, the choice would be difficult, particularly when the scientist is working as part of a research team managed by a competent and efficient project manager. The situation is seen not only in science but also in business management. The point is related to the classical managerial challenge of top down or bottom up management. If managerial power is transferred to the on-the spot director, he or she can fully desterilize uncodified and tacit knowledge and utilize managerial resources in the context of the actual situation. However, if a hierarchical managerial role is played top down, findings based on ground level intuition are seldom utilized. A centralized bureaucracy cannot readily adopt new ideas or easily adapt to environmental changes due to its formalization (Gouldner 1954, Merton 1957, Selznick 1949).

The third point concerns the effect of division of labor in research and management on research productivity. One of the advantages of a division of labor is the increased efficiency resulting from specialization and concentration on a single subtask. Thus, if a

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[1] Criticism has been presented from different perspectives. For instance, the massive scale of defense related funding channeled research in physics from basic to applied (Forman 1987). This paper does not suppose that the Big Science is favorable to progress in science and technology.

leading scientist is separated from a managerial role, he or she could focus on research and increase productivity. A specialized project manager can also be fully responsible for the progress of a research project. The top down hierarchical management facilitates completion of the original research goal. In other words, the second and third points touch the dilemma in management between exploration and exploitation (March 1991).

Through exploring the scientists' survey, this paper investigates the effects of science-management division on serendipity and productivity and presents the following. First, serendipity has a positive effect on citation. This is consistent with the anecdotal evidence suggesting that major scientific discoveries are likely to be serendipitous. Second, the integration of a managerial and leading research role has a positive effect on serendipity. However, this positive effect diminishes as the size of the research project increases. This implies that integration reduces coordination costs between management and actual research and provides flexibility in research to scientists, while the advantage of the division of labor in management and science increases as the project gets larger. Third, the separation of management from research has a larger positive effect on the number of papers as the project becomes bigger. These empirical results suggest a tradeoff between serendipity and productivity in science via who plays the managerial and leading research roles in research management.

In the next section, this paper defines serendipity and reviews previous literature on management of science, serendipity, and productivity. Next, it introduces the estimation strategy and data, which come from the scientists' survey, in detail. Then, it shows the estimated results, summarizes the findings, and shows policy and managerial implications.

2 Management and Serendipity

Research is rarely done in isolation; rather, research is increasingly being done by a team. For example, the mean number of authors per paper increased from 2.8 in 1981 to 4.2 in 1999 (Adams et al. 2005). Adams et al. (2005) observed that team size increased by 50% over a 19-year period. This trend continues. In the 1980s, the growth rate was 2.19%; that rate rose to 2.57% in the 1990s. By showing that scientific output and influence increase with team size, the authors imply that research productivity increases with the division of labor in research.

There are several factors behind this increasing trend in team size. Several studies have shown that collaborative research produces better outcomes with higher citation rates (Andrews 1979, Presser 1980, Sauer 1988, Wuchty et al. 2007). This suggests that interdisciplinary research has become increasingly important. The Internet and institutional change have decreased communication costs and promoted increasing team size (Agrawal and Goldfarb 2008). The increase of team size in scientific research in the U.S. has been attributed to the deployment of the National Science Foundation's NSFNET and its connection to networks in Europe and Japan after 1987 (Adams et al. 2005). Advancement of research equipment (e.g., cyclotron, particle accelerators, and high-flux research reactors) increases both collaboration and team size. The experimental design has also changed from table-top experiments to large-scale projects. This, too, accompanies changes in the pattern of collaborations among researchers because the new experimental tools require much different expertise.

Many researchers have suggested that diversity in a research team can lead to a greater level of creativity (Allen 1977, Garvey 1979, Kasperson 1978, Pelled et al. 1999). S. and F. (2010) suggested that collaboration reduces the probability of very poor outcomes because of more rigorous selection processes and greater recombinant opportunity in creative searches. Zuckerman (1977) showed that nearly two-thirds of the 286 Nobel Prize winners named between 1901 and 1972 were honored for work they did collaboratively. By investigating the conditions under which major discoveries or fundamental new knowledge occur in science, Hollingsworth (2006) stated that scientists are likely to develop new and alternative ways of thinking if they interact with scientists with diverse expertise and backgrounds. With the advancement of information and communication technology and institutional changes, scientists could obtain relevant but different knowledge by collaborating with other scientists in areas outside of their specialties. Accessing external complementary knowledge and expertise through networking becomes significant when promoting innovation not only in business, but also in science (Fleming et al. 2007, Hagedoorn 2002, Heinze et al. 2009, Powell et al. 1996).

The increase of team size and diversity suggests that management becomes important in science. Managing and coordinating research processes and different expertise and synchronizing efforts into a team goal do not happen naturally (Barnard 1938, Simon 1976). If the research team becomes larger and the research becomes more inter-disciplinary and inter-organizational, the role played by research management will be greater. For example, it is important to manage a certain space, called a “trading zone,” in which groups of different expertise learn to interact and deliver breakthroughs in science (Collins and Gorman 2007, Galison 1997).

Furthermore, competition in science becomes fiercer. The importance of priority in scientific discovery has risen (Ellison 2002, Stephan and Levin 1992). There is competition not only for priority in scientific discovery, but also for research funding. Thus, it is increasingly important for a research team to choose a research area and method and to set a research goal to minimize the threat of being “scooped” (Dasgupta and David 1994, Stephan and Levin 1992).

As research increasingly becomes large scale and requires a high level of technical and scientific knowledge, and competition becomes fiercer, management of science is becoming increasingly important. Following the division of labor and coordination costs framework (Becker and Murphy 1992), this paper, which considers the research team closely linked with specialization and the division of labor, explores the impact of management on performance in scientific research.

The word “serendipity” was coined by the novelist Horace Walpole, who was inspired by the Persian fairy tale, Three Princes of Serendip. Merton and Barber (2004) explored how the word unexpectedly won publicity without clear definition and fared from its 1754 coinage to the twentieth century. In scientific circles, the word has been used since the nineteenth century, when the importance of unplanned and accidental factors in the making of scientific discovery gained increasing recognition (Merton and Barber 2004). Serendipity has been often noted for its role in the work of inventors and entrepreneurs by persons such as George W. Merck, a president of Merck & Co., and Willis Whitney, a director of research of the General Electric Laboratories, the Pfizer Company (Merton and Barber 2004).

In the colloquial sense, serendipity is the making of happy and unexpected discoveries. Many anecdotal stories reveal how unintentional findings have yielded unexpectedly fortunate results. Many great discoveries, such as penicillin, X-rays, celluloid, and artificial sweetener, have been utterly fortuitous, making the concept of serendipity not well-operationalized (Roberts 1989, Shapiro 1986). It is uncertain whether the accidental nature of serendipity is linked with the nature of the discovery process or with the unexpected impact of the discovery. However, upon closer examination, it is obvious that the unplanned and accidental nature of serendipity has to do only with the discovery process. This is reflected in official definitions of the word. For instance, The American Heritage Dictionary of the English Language, fourth edition, defines serendipity as “the faculty of making fortunate discoveries by accident.” Furthermore, distinguishing between the unexpected and the accidental is difficult, especially when research involves exploration of the unknown.

Therefore, in order to operationalize the concept of serendipity, it is appropriate to think of serendipity as “the act of finding answers to questions not yet posed” (Stephan 2010). This definition focuses on not only the discovery process, but also on the relationship between discovery and the specific research question. Even though this definition directs its attention specifically to the extent that the discovery answers a question not yet posed, this paper adopts this definition and explores the relationship between management and serendipity in science.

3 Estimation Strategy

3.1 Hypotheses

This paper directs its attention to the managerial role played in a research team in order to explore the effect of management on serendipity and productivity in science research, focusing on three aspects. The first aspect examines the relationship between serendipity and research performance. Based on anecdotal evidence, we assume that serendipity improves the quality of research. Hence, our first hypothesis to be explored is the following:

H-1: *The existence of serendipity has a positive effect on quality of research*

The second aspect is related to the discussion about information asymmetry between management and research, which is closely related to the discussion on serendipity. Scientists possess specialized and domain-specific expertise. As previous literature on scientific discovery has expressed, the nature of scientific discovery is highly unpredictable (Polanyi 1962), and tacit and uncodified knowledge plays an important role in research, even though the outcomes of research are usually codified and published (Collins and Harrison 1975, Polanyi 1967). Learning is highly situated in the on-site context (Brown and Duguid 1991, Kogut and Zander 1992, Lave and Wenger 1991). When scientists are committed to actual research, they encounter unexpected observations and findings. Thus, if a managerial role on the research project team and a leading role in the actual research are played by different individuals, the research project will have information asymmetry between management and actual research. When a scientist observes unexpected but potentially creative serendipitous findings or encounters a serendipitous idea, he or she needs to encourage the person who plays a managerial role to change the initial research plan in order to pursue serendipity. Presenting a serendipitous encounter to a manager may be risky, particularly when the new idea or observation is contrary to accepted ways of doing or thinking about things (Pelz and Andrews 1966). Thus, even if a surprising fact or relation is observed, there may be a case in which it is not (optimally) investigated by the discoverer (Barber and Fox 1958, Van Andel 1992). In contrast, if a core scientist is also responsible for project management, the coordination and communication costs for shifting research to pursure serendipitous findings will be decreased. Hence, this paper investigates the following hypothesis:

H-2: *Serendipity is positively related to the integration of core-scientists from management*

However, if a core scientist plays a managerial role, the advantage of division of labor in science will not be fully realized. Efficiency is increased by specialization and concentration on a single subtask. Managing a research team and conducting research require different sets of expertise. Thus, it is possible to suppose that if a core scientist is separated from a managerial role, he or she can focus on the research. This is important, particularly for a large scale research project, which requires many bureaucratic procedures, paper work, and managerial tasks. This paper, therefore, explores the following hypothesis:

H-3: *Research productivity is positively related to the separation of core-scientists from management*

3.2 Data Description

We use the data from the scientists' survey conducted in the U.S. and Japan between 2009-2011 jointly by Hitotsubashi University; the National Institute of Science and Technology Policy (NISTEP) of the Ministry of Education, Culture, Sports, Science, and Technology;

and the Georgia Institute of Technology.[2] This survey collected approximately 2,100 responses from scientists in Japan and 2,300 responses from scientists in the U.S. regarding their research projects.[3] The population of the survey was comprised of articles and letters in the Web of Science database of Thomson Reuters. Review papers were excluded from the population. The time window of the papers for the survey was from 2001 to 2006 (database year), during which time the published papers were recorded in the Web of Science database. The bibliographic information and the number of citations as of the end of December 2006 were used in the survey. This survey selected two sets of focal papers from the population. The first was "Highly Cited" Papers (H paper), which consisted of the top 1% highly cited papers in each journal field (22 fields in total) and from each database year. The other set was "Normal" Papers (N paper), or randomly selected papers in each journal field and in each database year from the population of the survey, excluding highly cited papers. Roughly one-third of the samples were from highly cited papers (top 1% in the world) in each science field; the rest were from randomly selected papers.

The survey asked questions about the following topics: the knowledge sources which inspired the projects; uncertainty in the knowledge creation process; research competition; composition of the research team; sources of research funding; the research outputs, including papers, patents, and licenses; and the profile of scientists. The survey specifically addressed managerial roles and serendipity, to which this paper directs its attention, as well. The survey asked the corresponding author of the focal paper his role in management of the research project and research implementation. As for the exitence of serendipity, this survey asked: "Has the research output found the answers to questions not originally posed (in other words, was the research output serendipitous)?" Approximately 55% of respondents answered his/her main finding was obtained through serendipity.[4] In the Appendix, we provide the list of these threee questions and responses reported in the survey.

3.3 Estimation Methodology

To examine our three hypotheses, we employ the following estimation methods respectively.

H-1 model investigates the relationship between serendipity and research quality. Remarkably, a simple regression shows no significant relation between serendipity and performance. However, we argue that this insignificant relationship is caused by the endogeneity between serendipity and research performance. A research team pursues publication only when it considers it to be valuable. Hence, the observed citation rate might reflect not only the fact that a serendipitous event has uncovered in research, but also the research

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[2] See Nagaoka et al. (2011) for the detailed results.

[3] The overall response rate was 27% in Japan and 26% in the U.S.

[4] Approximately 61% of respondents in the field of Computer Science reports serendipity, which is the largest fraction among all the fileds. In contrast, only 42% of social scientists reports serendipity.

team's ex ante evaluation of that discovery. For this reason, we use a Two-Stage Least Squares (2SLS). In addition, since the survey oversampled the top 1% highly cited papers and our dependent variable, the number of citations, correlates with this biased sampling, we need to appropriately weight each sample. These two problems are explained in detail in the following section.

We conduct probit regression for the H-2 model since the dependent variable, the existence of serendipity, is a binary. One crucial problem with probit regression is its fragility to heteroskedasticity of the error term. Hence, we test whether our results are robust to the misspecification of the error term, and claim that our hypothesis still holds.

For the H-3 model, in which the relationship between research productivity and the degree of management-research integration is examined, we use a Negative Binomial (NB) regression with assuming that the variance of dependent variable takes quadratic form.[5] Since research productivity is measured by the number of papers produced by the entire research project, our dependent variable is necessarily discrete, and its empirical distribution concentrates at 1. For these reasons, we choose the NB regression model.[6] Since the estimate of the NB regression coincides with that of quasi-maximum likelihood, the estimator is robust to misspecification of the distribution of the dependent variable. That is, the NB regression yields a consistent estimator as long as the specification of the conditional expectation of regressand is correct.[7]

3.4 Definition of Variables

This section introduces the definitions of variables used in our models. Table 2 presents a complete list of variables and their definitions, and Table 3 shows summary statistics of all variables.

3.4.1 Dependent Variables

Different models adopt different dependent variables, respectively. To measure research productivity, we use the number of articles published by the entire research project. Research quality is measured by the total number of citations by 2009.[8] H-2 model uses the existence of serendipity as a dependent variable. This variable takes one if a respondent answered that his main findings were obtained through serendipity.

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[5] More specifically, we use a zero-truncated NB regression, in which the dependent variable is truncated at zero. This is because we only have data on research projects that published at least one paper.

[6] Poisson regression may not be suitable in our case since the equi-dispersion hypothesis is strongly rejected (at the 1% significant level).

[7] See Cameron and Trivedi (2005) for its textbook treatment. Also, see Ding et al. (2010) for an application in a related context.

[8] Some papers might considerably increase citation numbers after 2009. But since 70% of papers in 2008 increased by less than 10 in their citation number from 2007, we think that the total number of citations by 2009 can be a reasonable approximation.

3.4.2 Independent Variables

Management structure is measured by two mutually exclusive variables. *Integration* is a dummy variable that indicates one only if the researcher takes a leading role in the research management, designing the research project, organizing the research team, and/or acquiring research funds. On the other hand, *separation* is a dummy variable that indicates one only if the researcher plays no management role.[9]

Variables that describe a research project's characteristics are *project size, project duration, fund size, competitor threat*, and *inter-organizational communication. Project size* is a number of people involved in the project, which includes corroborative researchers (excluding coauthors), graduate students, undergraduates, and technicians. Since not all projects had been terminated by the time of the survey, *project duration* is calculated by subtracting the year when the project started from the year of the most recent corresponding publication. *Fund size* is the total sum of research funds prepared for the project. *Competitor threat* is a binary variable and takes one only if the researcher considered the possibility of competitors who may have had priority over the research results. If the project developed a community of researchers beyond the original laboratory, *inter-organizational communication* indicates one, otherwise it takes zero.

Scientists are classified by the following characteristics: *age, degree, past awards, past transfers, past publications*, *affiliation*, and *country. Age* is respondent's age at the time of the survey. *Degree* is shown as one if the researcher has a Ph.D. or equivalent degree. *Award* is a binary variable that takes one if the researcher received a distinguished paper award or a conference award. If the respondent had changed academic or research position across organizations before the survey, *past tranfers* takes on the value of one. *Past publication* measures the number of referred papers in English published from 2006 to 2008. *Affiliation* equals one if the respondent works for universities. *Country* shows one for the respondents in the U.S. and shows zero for the respondents in Japan.

We control the respondent's research field based on the survey's classification. Table 1 shows a correspondence between its classification and the 22 ESI journal fields. All scientific areas are divided into ten fields: Chemistry, Materials Science, Physics & Space Science, Computer Science & Mathematics, Engineering, Environment/Ecology & Geosciences, Clinical Medicine & Psychiatry/Psychology, Agricultural Sciences & Plant & Animal Sciences, Basic Life Sciences, and Social Sciences.[10] We also take into account each researcher's research skill, as well as his or her specialty in theory or experimentation.

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[9] Hence, both variables taking zero means that a researcher is involved in management to some extent.

[10] Social Sciences may be a fairly broad field compared to other categories. However, since about 95% of respondents are natural scientists, this makes no significant difference.

3.5 Estimation Issues

3.5.1 Endogeneity Bias

Serendipity is likely to be endogenous in the following sense. It is reasonable to assume that a scientific finding is pursued only when the researcher evaluates its quality and then believes that it is worth pushing forward. If so, there can be two directions of endogenous effects from the measured citation to the reported serendipity. The first possibility is that the researcher may be less experienced in the field in which serendipity occurs than in his or her field of expertise; hence, the finding seems more novel to the researcher, who overestimates the value of the serendipitous finding. The second possibility is that the researcher pursues his/her serendipitous finding only if it is highly valuable, since shifting research direction seems more risky. We cannot determine which path of endogenity dominates the other, but both hypotheses suggest that, without crowding out the correlation between the existence of serendipity and the researcher's ex-ante evaluation of serendipitous finding, we underestimate or overestimate the effect of serendipity on research quality. Indeed, in H-1 model, the result of the variable addition test rejects the hypothesis that serendipity is an exogenous variable at the 5% significance level.

We use instrumental variables to deal with this problem.[11] Here, instrumental variables must correlate with the existence of serendipitous findings, but they must not affect the ex-ante evaluation of findings. With this criterion, we instrument serendipity with two variables, *skill diversity* and *knowledge inflow*. *Skill diversity* is a dummy variable that becomes one if the researcher stated that it was very important to communicate with researchers who have different research skills, for example, experimental researchers communicating with theorists. *Knowledge inflow* is also a dummy variable that becomes one if the researcher stated that it was very important to communicate with visiting researchers or postdoctoral researchers in his or her organization. Serendipity is highly likely to correlate with these two variables, since complementarity in knowledge and skills are key to improving creativity. Our argument is supported, for example, by Heinze et al. (2009), who observed that the most important types of communication to inspire a researcher's creativity includes specialists who are equipped with knowledge or skills that the researcher himself does not possess. We assume that these instruments and the ex-ante evaluation of findings are uncorrelated, since the former is related to the entire project, not only to the focal paper.[12]

3.5.2 Sampling Bias

One-third of the samples are randomly chosen from researchers who wrote a top 1% highly cited paper. Hence, our samples are not randomly drawn from the entire population. We

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[11] Angrist and Pischke (2008) provides a lengthy treatment on how to take advantage of instrumental variables from a practitioner's view.

[12] As a robustness check, we also examine other instrument variables. Results are reported in Table 8.

must consider this problem to yield a consistent estimator for the H-1 model, since the stratification depends on the regressand (i.e., the number of citations). Ignoring this endogenous stratification yields biased estimator.

A straightforward provision for this problem is to introduce a weighting matrix whose i th diagonal element is Qj_i/Hj_i, where the numerator is the probability that a randomly drawn observation from the population falls into stratum j and the denominator is the fraction of observations in stratum j for each observation i.[13] Under reasonable regularity conditions, this weighted least squares estimator is ensured to be consistent and asymptotically normally distributed.[14] Also, with a slight modification on White's (1980) heteroskedasticity-consistent covariance matrix, a consistent estimator of covariance matrix can be obtained.

4 Results

4.1 Baseline Estimates

We first summarize results on the H-1 regression. In this model, our unit of analysis is a focal paper, not the entire research project. Moreover, we only use observations for which the respondent is the first author of the focal paper. Table 4 shows the estimation result. We observe that serendipity has a positive effect on the number of citations at the 5% significance level in the 2SLS regression. This confirms our hypothesis H-1. We also note in Table 4 that the research quality is high when the researcher perceives the threat from competition, has experienced transfer between institutions, or has a strong publication record. In addition, the integration of management and research may have a positive effect on the research quality by offsetting the negative effect of increasing project size. Along with the estimated effect of past transfer, this observation may be consistent with the recent literature which argues that researchers who have more opportunities to communicate with other researchers tend to show higher creativity (Fleming et al. 2007, Powell et al. 1996).

Model H-2 examines the connection between management structure and serendipity. In Table 5, the column labeled "Model 2-1" exhibits the result of the probit regression for H-2. We observe that the integration of management has a positive effect on serendipity. However, the effect tends to attenuate as the project size increases. That is, the integration of management encourages researchers to pursue the serendipitous idea more often, only when management tasks are not too intense. Moreover, estimates in Table 5 indicate that serendipity is reported more often when the researchers are more open to knowledge inflow from visiting researchers and post-doctoral researchers, or to communication with researchers with different skill sets and outside their own laboratories. This result also

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[13] In our regressions, we have only two stratum, and weights are 0.032 for samples from the highly cited group, and 1.433 for others.

[14] For the formal treatment, see Wooldridge (2010a,b).

justifies our use of instrumental variables.

The regression results of model H-3 are shown in Table 6. The unit of analysis here is the entire research project, unlike previous regressions. This is because H-3 is concerned with the effect of management structure on the productivity of the entire project. We use observations for which the respondent was the researcher who took a central role of the research and contributed the most. Our hypothesis is that the separation of management from research increases research productivity. The estimates reported in Table 6 conform to the hypothesis. Note that all coefficients in Table 6 can be interpreted as a semielasticity. The estimate of the interaction term between separation of management and project size is negative. However, since the estimate of the interaction term between separation of management and the squared project size is positive, as the project size gets bigger, separation increases the number of papers. That is, separating management from research is beneficial only when management is strongly needed.

4.2 Robustness Checks

We conduct various robustness checks. First, since the variance of citation number can be significantly different across fields, we standardize the citation by dividing the dependent variable of H-1 model, $\ln(cite2009)$, by its standard deviation by field. The results shown in Table 7 indicate that the estimates are qualitatively unchanged. In addition, we test the validity of our choice of instrumental variables. Four different choices are examined: *skill diversity* (Model 1-1), *knowledge inflow* (Model 1-2), *inter-organizational communication* and *skill diversity* (Model 1-3), and *inter-organizational communication* and *knowledge inflow* (Model 1-4). Table 8 shows the results respectively. Though some estimates show somewhat weaker coefficient, all of the four models imply that serendipity and the number of citations are positively correlated, so that our hypothesis is maintained.

Second, for the H-2 probit, we test the robustness to the heteroskedasticity of the error term. Now the error term is assumed to be heteroskedastic with a variance of

$$\sigma_i^2 = \exp(z_i \delta),$$

where z_i is an exogenous variable. We choose two candidates for z_i, *project duration* and *research fund*. In both cases, the likelihood-ratio test rejects the hypothesis that the error term is homoskedastic at the 5% significance level. Models 2-2 and 2-3 in Table 5 show these results, and all the results are still consistent with our hypothesis.

Finally, we alter the dependent variable in model H-3 to the number of referred papers in all languages instead of only in English. The estimates in Table 6 show that all the important results of this paper are still qualitatively unchanged.

5 Conclusion

This paper has investigated the influence of management-science integration on serendipity and productivity in scientific research. The major estimated results show that the integration of a managerial and a leading research role has a positive effect on serendipity. However, this effect diminishes as the project increases in size and scope. This implies that integration reduces coordination costs between management and research and provides flexibility in research to scientists, while the advantage of the division of labor in management and science increases as the project size increases. It also shows that the separation of management from research has a larger, positive effect on the number of papers as the project becomes bigger. These results show the tradeoff between serendipity and productivity in science via who plays the managerial role and leading research role in research management.

Serendipity plays an essential role in discoveries not only in science, but also in technology, management, business practices, art, and daily life (Jacobs 2010, Svensson and Wood 2005, Van Andel 1992). This paper examines management and research in science, and its findings have implications for corporate R&D and university research administrators. The findings of this paper imply that bureaucratic coordination, which enlarges information asymmetry and incommensurability between management and research, profits from serendipitous encounters. It is quite consistent with contingency theory between complexity of environment (e.g., demand, strategic positioning, and technology) and organizational structure (Burns and Stalker 1961, Lawrence and Lorsch 1967, Scott 1981). Decentralized and less formalized management that allows a high degree of flexibility is suitable when an organization faces many exceptional problems and problem solving is not easy (Perrow 1967, Woodward 1965). This suggests that decision-making should be done where important information is gathered and knowledge is created if environmental change is uncertain but highly frequent. The more embedded the knowledge, the greater autonomy of the R&D unit (Birkinshaw et al. 2002). However, operational administrators are usually trained to complete the project's goal. In fact, they attempt to manage in a way that will eliminate uncertainty in their affairs so that they can meet budgets and target deadlines (Udwadia 1990). This may be one of the reasons that it is difficult for corporate R&D overseen by a central business manager to profit from serendipitous findings at the laboratory. It suggests that Alexander Fleming would have faced difficulties in changing his original research plan to pursue the serendipitous findings if he had been working in a corporate laboratory and his research had been led by a competent project manager. In other words, Fleming would have not pursued the serendipitous findings, but he would have delivered more papers concerning the original research project if a managerial role had been played by a specialized director. It also suggests that it is quite important for a university research administrator to fully understand the nature of discovery in science and the tradeoff between serendipity and productivity in science via who plays the managerial and leading research roles in research management (Kaplan 1959, Kulakowski and Chronister 2006).

To conclude this paper, we mention some limitations that future research should address more explicitly. A key result suggests that if scientific research is bureaucratically controlled in a research organization, serendipitous encounters will not be realized. In other words, even when a managerial role and a leading research role are played by different people, serendipity will be realized if a manager shares tacit and domain-specific knowledge with leading scientists and understands the nature of scientific discovery. This paper presupposes a certain degree of incommensurability, which was proposed by "Khunian paradigm arguments" (Kuhn 1970) between a manager and leading scientists. However, the degree of incommensurability depends on a manager's expertise and capabilities. Since the scientists' survey does not allow investigating a manager's capabilities, this paper does not explore the quality of managers in a research organization. Organizations for university research administrators such as SRA (Society of Research Administrators), NCURA (National Council of University Research Administrators) in the U.S., and ARAM (Association of Research Managers and Administrators) in the U.K, has been established since the 1960s. And not only these organizations but also governments (e.g., the Development of a Research Administration System program launched by Ministry of Education, Culture, Sports, Science, and Technology-Japan) are beginning to consider that a managerial role should be played by a specialist who can share tacit and domain-specific knowledge with leading scientists; scientists could then focus on large-scale research projects, which could have managerial flexibility for realizing serendipitous encounters. Previous literature on how scientists with different expertise and different paradigms communicate has indicated that scientists communicate in groups called "trading zones" where they can agree on rules of exchange, learn language, and share tacit knowledge (Collins and Gorman 2007, Galison 1997, 1999). However, since the extent to which managers and scientists can reduce the degree of incommensurability depends on a manager's ability, it is important to explore a manager's expertise and capabilities on the research outcome in detail.

Table 1: List of Fields

22 ESI Journal Fields	10 Fields	Number of Papers	Percentage
Agricultural Sciences	Agricultural Sciences & Plant & Animal Science	349	7.9
Plant & Animal Science			
Biology & Biochemistry	Basic Life Science	910	20.6
Immunology			
Microbiology			
Neuroscience & Behavior			
Pharmacology & Genetics			
Chemistry	Chemistry	441	10.0
Clinical Medicine	Clinical Medicine & Psychiatry/Psychology	710	16.1
Psychiatry/Psychology			
Computer Science	Computer Science & Mathmatics	208	4.7
Mathmatics			
Economics & Business	Social Sciences	250	5.7
Social Science, general			
Engineering	Engineering	368	8.3
Environment/Ecology	Environment/Ecology & Geosciences	308	7.0
Geosciences			
Material Science	Material Science	214	4.9
Multidisciplinary	(Journal field was assigned based on the analysis of the backward citations)	13	0.3
Physics	Physics & Space Science	639	14.5
Space Science			
Total		4410	100

Table 2: Definitions of Variables

Variable	**Definition**
serendipity	Equals one if his/her main findings are obtained through serendipity.
# of published papers	The number of papers published in a research project.
# of citation	Cumulative number of citations in 2009.
project size	Sum of the number of corraborative researchers, graduate students, undergraduates, and technicians involved in the project.
project duration	Years since the research project was launched.
research fund	The total sum of research funds prepared for the project.
separation	Takes one if the researcher takes a leading role in the research management, designing the research project, organizing the research team, and/or acquiring research funds.
integration	Takes one if the researcher plays no managment role.
competitor threat	Takes one if the researcher considered the possibility of competitors who may have had priority over the research results.
skill diversity	Takes one if the researcher states that communication with researchers who have different research skills was important for conceiving the research project.
knowledge inflow	Takes one if the researcher states that communication with visiting researchers or postdoctoral researchers was important for conceiving the research project.
inter-org comm	Takes one if the researcher built a research community beyond own laboratory.
past publication	The number of referred papers in English that the researcher published from 2006 to 2008.
degree	Takes one if the researcher has a Ph.D. or equivalent degree.
award	Takes one if the researcher received a distinguished paper award or a conference award.
age	Respondent's age at the time of survey.
year in paper	The amount of years to publish the paper.
affiliation	Takes one if the researcher works for universities.
country	Takes one for the respondents in the U.S. and shows zero for the respondents in Japan.
theory	Takes one if the researcher specializes in theoretical work.
experiment	Takes one if the researcher specializes in experiments.

Table 3: Summary Statistics

Variable	Mean	Std. Dev.	Min.	Max.	N
serendipity	0.558	0.497	0	1	4401
# of published papers	15.012	39.889	1	900	4334
# of citation	59.009	108.288	1	2034	4343
project size	4.386	19.706	0	600	3804
project duration	6.988	4.903	0	47	3420
research fund ($)	1894156	11167946	0	300×10^6	4288
separation	0.062	0.241	0	1	4408
integration	0.696	0.46	0	1	4408
competitor threat	1.089	1.878	0	5	4408
skill diversity	0.589	0.492	0	1	4408
knowledge inflow	0.552	0.497	0	1	4408
inter-org comm	0.555	0.497	0	1	4408
past publication	25.853	46.786	0	750	4330
degree	0.134	0.628	0	4	4337
award	0.377	0.485	0	1	4249
age	51.452	10.264	16	91	4286
country	0.528	0.499	0	1	4408
year in paper	2.956	3.302	0	38	4045
affiliation	0.731	0.444	0	1	4408
theory	0.193	0.395	0	1	4408
experiment	0.652	0.476	0	1	4408

Table 4: Effect of Serendipity on Research Quality

	OLS		2SLS	
serendipity	0.0341	(0.0727)	1.4209**	(0.6224)
project size	-0.0305**	(0.0128)	-0.0401***	(0.0150)
separation	-0.2654	(0.1939)	-0.3046	(0.2160)
separation×pj size	-0.0084	(0.0908)	-0.0309	(0.1054)
separation×(pj size)^2	0.0042	(0.0065)	0.0055	(0.0078)
integration	-0.0699	(0.1124)	-0.1832	(0.1370)
integration×pj size	0.0307**	(0.0133)	0.0381**	(0.0155)
integration×(pj size)^2	-0.0000	(0.0000)	0.0000	(0.0000)
year in paper	-0.0132	(0.0255)	-0.0345	(0.0304)
(year in paper)^2	-0.0005	(0.0015)	-0.0003	(0.0017)
competitor threat	0.0786***	(0.0202)	0.0586**	(0.0245)
ln(fund)	0.0498**	(0.0210)	0.0304	(0.0260)
age	-0.0647**	(0.0294)	-0.0361	(0.0360)
(age)^2	0.0005*	(0.0003)	0.0002	(0.0003)
degree	-0.0515	(0.0454)	-0.0372	(0.0519)
award	0.0140	(0.0769)	-0.0061	(0.0897)
past move	0.0944	(0.0758)	0.2075**	(0.0980)
past publication	0.0030***	(0.0009)	0.0023**	(0.0010)
country	0.2944***	(0.0883)	0.6487***	(0.1873)
affiliation	-0.1675**	(0.0849)	-0.1968**	(0.0989)
theory	0.0315	(0.1339)	0.0618	(0.1588)
experiment	0.1508	(0.1140)	0.1671	(0.1370)
Observations	1405		1405	
F-statistic	25.9377		5.5658	

Standard errors in parentheses * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note: Researcher's fields are controlled but results are not reported.
fund is the average amount of fund per paper.

Table 5: Effect of Management Structure on Serendipity

	Model 2-1		Model 2-2		Model 2-3	
project size	0.0077	(0.0049)	0.0073	(0.0060)	0.0077	(0.0066)
separation	0.0438	(0.0616)	0.0097	(0.0705)	0.0541	(0.0604)
separation×pj size	0.0076	(0.0128)	0.0225	(0.0187)	0.0074	(0.0146)
integration	0.0769**	(0.0387)	0.0886**	(0.0392)	0.0744*	(0.0389)
integration×pj size	-0.0082*	(0.0050)	-0.0076	(0.0060)	-0.0082	(0.0066)
knowledge sharing	0.0720**	(0.0284)	0.0773***	(0.0262)	0.0625**	(0.0291)
skill diversity	0.1106***	(0.0266)	0.0627**	(0.0290)	0.1117***	(0.0255)
inter-org comm	0.0926***	(0.0289)	0.0914***	(0.0308)	0.0948***	(0.0293)
year in paper	0.0101	(0.0085)	-0.0174***	(0.0065)	0.0122	(0.0089)
(year in paper)^2	0.0001	(0.0005)	0.0008***	(0.0003)	-0.0001	(0.0005)
competitor threat	0.0115*	(0.0069)	0.0042	(0.0070)	0.0114*	(0.0067)
ln(fund)	0.0077	(0.0071)	0.0145**	(0.0068)	0.0148*	(0.0083)
age	-0.0142	(0.0113)	-0.0080	(0.0097)	-0.0124	(0.0108)
(age)^2	0.0002	(0.0001)	0.0001	(0.0001)	0.0001	(0.0001)
degree	-0.0024	(0.0167)	-0.0012	(0.0172)	-0.0013	(0.0162)
award	0.0147	(0.0273)	-0.0055	(0.0261)	0.0064	(0.0267)
past publication	0.0005	(0.0004)	-0.0002	(0.0002)	0.0006	(0.0005)
past move	-0.0391	(0.0262)	-0.0127	(0.0258)	-0.0278	(0.0262)
country	-0.3117***	(0.0330)	-0.2429***	(0.0422)	-0.3006***	(0.0326)
affiliation	0.0092	(0.0294)	0.0065	(0.0261)	0.0151	(0.0293)
theory	-0.0182	(0.0495)	0.0121	(0.0484)	-0.0182	(0.0495)
experiment	-0.0046	(0.0414)	0.0158	(0.0382)	-0.0021	(0.0415)
Observations	1435		1265		1435	
Log Likelihood	-881.1193		-768.8073		-878.7751	

Standard errors in parentheses * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note: All coefficients are average marginal effect.

Researcher's fields are controlled but results are not reported.

fund is the average amount of fund per paper.

Table 6: Effect of Management Structure on Research Productivity

	English Papers		All Referred Papers	
project size	-0.0075	(0.0154)	0.0090	(0.0134)
separation	0.1898	(0.1966)	0.2454	(0.1843)
separation×pj size	-0.2530***	(0.0980)	-0.2336***	(0.0907)
separation×(pj size)^2	0.0246***	(0.0075)	0.0224***	(0.0070)
integration	-0.0051	(0.1120)	0.0268	(0.1035)
integration × pj size	0.0245	(0.0156)	0.0086	(0.0136)
integration × (pj size)^2	-0.294×10^{-4}***	(0.0000)	-0.297×10^{-4}***	(0.0000)
project duration	0.0940***	(0.0166)	0.1099***	(0.0157)
(project duration)^2	-0.0009	(0.0006)	-0.0014**	(0.0006)
competitor threat	0.0681***	(0.0161)	0.0562***	(0.0151)
inter-org comm	0.2555***	(0.0778)	0.3154***	(0.0730)
ln(fund)	0.2060***	(0.0168)	0.1739***	(0.0154)
past publication	0.0056***	(0.0009)	0.0047***	(0.0008)
country	-0.5821***	(0.0863)	-0.8596***	(0.0811)
award	0.0960	(0.0679)	0.1467**	(0.0646)
degree	-0.0426	(0.0487)	-0.0638	(0.0456)
affiliation	-0.1516**	(0.0759)	-0.2236***	(0.0707)
Observations	1731		1731	
Log Likelihood	-5933.2799		-6241.8738	

Standard errors in parentheses * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note: All coeficients are semielasticity.

Researcher's fields are controlled but results are not reported.

Table 7: Effect of Serendipity on Research Quality with Standardization

	OLS		2SLS	
serendipity	0.0155	(0.0437)	0.8285**	(0.3707)
project size	-0.0173**	(0.0074)	-0.0230***	(0.0087)
separation	-0.1562	(0.1135)	-0.1792	(0.1259)
separation×pj size	-0.0102	(0.0532)	-0.0234	(0.0617)
separation×(pj size)^2	0.0028	(0.0038)	0.0036	(0.0046)
integration	-0.0351	(0.0669)	-0.1015	(0.0813)
integration×pj size	0.0175**	(0.0077)	0.0218**	(0.0090)
integration×(pj size)^2	-0.0000	(0.0000)	0.0000	(0.0000)
year in paper	-0.0084	(0.0154)	-0.0209	(0.0182)
(year in paper)^2	-0.0003	(0.0009)	-0.0002	(0.0010)
competitor threat	0.0471***	(0.0120)	0.0353**	(0.0146)
ln(fund)	0.0325**	(0.0127)	0.0212	(0.0154)
age	-0.0384**	(0.0176)	-0.0216	(0.0215)
(age)^2	0.0003*	(0.0002)	0.0001	(0.0002)
degree	-0.0262	(0.0270)	-0.0178	(0.0307)
award	0.0118	(0.0464)	0.0000	(0.0537)
past move	0.0568	(0.0457)	0.1231**	(0.0586)
past publication	0.0018***	(0.0005)	0.0013**	(0.0006)
country	0.1721***	(0.0532)	0.3798***	(0.1111)
affiliation	-0.0986*	(0.0507)	-0.1158**	(0.0587)
theory	0.0195	(0.0818)	0.0372	(0.0960)
experiment	0.0925	(0.0695)	0.1020	(0.0827)
Observation	1405		1405	
F-statistic	18.4617		6.7746	

Standard errors in parentheses * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note: Researcher's fields are controlled but results are not reported. *fund* is the average amount of fund per paper.

Table 8: Robustness Test Using Alternative Instruments

	Model 1-1		Model 1-2		Model 1-3		Model 1-4	
serendipity	1.308*	(0.678)	1.721*	(1.037)	1.122**	(0.530)	1.186*	(0.625)
project size	-0.039***	(0.015)	-0.042**	(0.017)	-0.038***	(0.014)	-0.038***	(0.015)
separation	-0.301	(0.211)	-0.313	(0.231)	-0.296	(0.205)	-0.298	(0.208)
sep×pj size	-0.029	(0.103)	-0.036	(0.113)	-0.026	(0.100)	-0.027	(0.101)
sep×(pj size)^2	0.005	(0.008)	0.006	(0.008)	0.005	(0.007)	0.005	(0.007)
integration	-0.174	(0.136)	-0.208	(0.160)	-0.159	(0.127)	-0.164	(0.131)
inte×pj size	0.038**	(0.015)	0.040**	(0.017)	0.037**	(0.015)	0.037**	(0.015)
inte×(pj size)^2	0.000	(0.000)	0.000	(0.000)	-0.000	(0.000)	0.000	(0.000)
year in paper	-0.033	(0.030)	-0.039	(0.034)	-0.030	(0.029)	-0.031	(0.029)
(year in paper)^2	-0.000	(0.002)	-0.000	(0.002)	-0.000	(0.002)	-0.000	(0.002)
competitor threat	0.060**	(0.025)	0.054*	(0.028)	0.063***	(0.023)	0.062***	(0.024)
ln(fund)	0.032	(0.026)	0.026	(0.030)	0.035	(0.024)	0.034	(0.025)
age	-0.038	(0.036)	-0.030	(0.041)	-0.042	(0.033)	-0.041	(0.034)
(age)^2	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)
degree	-0.038	(0.051)	-0.034	(0.055)	-0.040	(0.049)	-0.040	(0.050)
award	-0.004	(0.088)	-0.010	(0.096)	-0.002	(0.085)	-0.003	(0.086)
past move	0.198**	(0.100)	0.232*	(0.121)	0.183**	(0.092)	0.188**	(0.096)
past publication	0.002**	(0.001)	0.002*	(0.001)	0.002**	(0.001)	0.002**	(0.001)
country	0.620***	(0.197)	0.725**	(0.288)	0.572***	(0.162)	0.589***	(0.184)
affiliation	-0.194**	(0.097)	-0.203*	(0.107)	-0.191**	(0.094)	-0.192**	(0.095)
theory	0.059	(0.156)	0.068	(0.170)	0.055	(0.150)	0.057	(0.152)
experiment	0.166	(0.134)	0.171	(0.145)	0.164	(0.130)	0.164	(0.131)
Observations	1405		1405		1405		1405	
F-statistic	5.813		4.728		6.453		6.194	

Standard errors in parentheses * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note: Researcher's fields are controlled but results are not reported.

fund is the average amount of fund per paper.

Appendix: Selected Survey Questions and Responses

Question: *Has the research output found the answers to questions not originally posed?*

	Response Rates	
Answers	Highly Cited	Normal
Yes	59.9%	54.0%
No	40.1%	46.0%

Question: *Please indicate which of the following best describes your role in the management of the research project.*

	Response Rates	
Answers	Highly Cited	Normal
(1) A leading role in the research management, designing the research project, organizing the research team, and/or acquiring research funds	70.9%	69.2%
(2) A member of the research management, but a role less than that of the leader	14.1%	14.8%
(3) No managerial role	7.2%	5.8%
(4) Management was not necessary	5.8%	8.0%
(5) Other	2.1%	2.3%

Question: *Please indicate which of the following best describes your role in the research implementation.*

	Response Rates	
Answers	Highly Cited	Normal
(1) I executed the central part of the research and contributed the most to the research output	64.4%	65.5%
(2) I took part in the central part of the research, but my contribution was not as substantial as that of the central researcher	20.8%	21.9%
(3) I implemented the research under the guidance of the above members	2.1%	3.0%
(4) I contributed to the research through the provision of materials, data, equipment, or facilities	2.7%	2.8%
(5) Other	10.0%	6.8%

References

Adams, J. D., C. B. Grant, R. J. Clemmons, P. E. Stephan. 2005. Scientific teams and institutional collaborations: Evidence from U.S. universities. 1981-1999. *Res. Policy* **34**(3) 259–285.

Agrawal, A., A. Goldfarb. 2008. Restructuring research: Communication costs and the democratization of university innovation. *Amer. Econom. Rev.* **98**(4) 1578–1590.

Allen, T. J. 1977. *Managing the flow of technology: technology transfer and the dissemination of technological information within the R&D organization*. MIT Press, Cambridge, Mass.

Andrews, F. M. 1979. *Scientific productivity : the effectiveness of research groups in six countries*. Cambridge University Press, Cambridge.

Angrist, J. D., J. S. Pischke. 2008. *Mostly Harmless Econometrics - An Empiricist's Companion.*. Princeton University Press, Princeton, New Jersey.

Austin, M. A., M. S. Hair, S. M. Fullerton. 2012. Research guidelines in the era of large-scale collaborations: An analysis of genome-wide association study consortia. *Amer. J. Epidemiology* **175**(9) 962–969.

Barber, B., R. C. Fox. 1958. The case of the floppy-eared rabbits: An instance of serendipity gained and serendipity lost. *Amer. J. Sociol.* **64**(2) 128–136.

Barnard, C. I. 1938. *The Functions of the Executive*. Harvard University Press, Cambridge, Mass.

Becker, G. S., K. M. Murphy. 1992. The divison of labor, coordination costs, and knowledge. *Quart. J. Econom.* **107**(4) 1137–1160.

Birkinshaw, J., R. Nobel, J. Ridderstråle. 2002. Knowledge as a contingency variable: Do the characteristics of knowledge predict organization structure? *Organ. Sci.* **13**(3) 274–289.

Brown, J. S., P. Duguid. 1991. Organizational learning and communities-of-practice: Toward a unified view of working, learning, and innovation. *Organ. Sci.* **2**(1) 40–57.

Burns, T. B., G. M. Stalker. 1961. *The management of innovation*. Tavistock Publications.

Cameron, C. A., P. K. Trivedi. 2005. *Microeconometrics: Methods and Applications*. Cambridge University Press, Cambridge, Mass.

Collins, Evans R., H., M. Gorman. 2007. Trading zones and interactional expertise. *Stud. in Hist. and Philo. of Sci.* **38** 657–666.

Collins, H., R. G. Harrison. 1975. Building a tea laser: The caprices of communication. *Social Stud. of Sci.* **5**(4) 441–450.

Dasgupta, P., P. David. 1994. Toward a new economics of science. *Res. Policy* **23**(5) 487–521.

Ding, W. W., S. G. Levin, P. E. Stephan, A. E. Winkler. 2010. The impact of information technology on academic scientists' productivity and collaboration patterns. *Management Sci.* **56**(9) 1439–1461.

Ellison, G. 2002. Evolving standards for academic publishing: A Q-R theory. *J. Polit. Econom.* **110**(5) 994–1034.

Fleming, L., S. Mingo, D. Chen. 2007. Collaborative brokerage, generative creativity, and creative success. *Admin. Sci. Quart.* **52**(3) 443–475.

Forman, P. 1987. Behind quantum electronics: National security as basis for physical research in the united states, 1940-1960. *Hist. Stud. in the Phys. and Bio. Sci.* **18**(1) 149–229.

Galison, P. 1997. *Image and logic : a material culture of microphysics*. University of Chicago Press, Chicago, Ill. ; London.

Galison, P. 1999. *Trading Zone: Coordinating Action and Belief*. Routledge, New York, 137–160.

Garvey, W. D. 1979. *Communication : the essence of science : facilitating information exchange among librarians, scientists, engineers and students*. Pergamon, Oxford.

Gouldner, A. W. 1954. *Patterns of Industrial Bureaucracy*. Free Press, Glencoe, Ill.

Hagedoorn, J. 2002. Inter-firm R&D partnerships: an overview of major trends and patterns since 1960. *Res. Policy* **31**(4) 477–492.

Heinze, T., P. Shapira, J. M. Senker. 2009. Organizational and institutional influences on creativity in scientific research. *Res. Policy* **38**(4) 610–623.

Hollingsworth, R. J. 2006. *The Dynamics of American Science: An Institutional and Organizational Perspective on Major Discoveries*. Campus Verlag, Frankfurt, New York, 361–380.

Jacobs, B. A. 2010. Serendipity in robbery target selection. *British J. Criminology* **50**(3) 514–529.

Kaplan, N. 1959. The role of the research administrator. *Admin. Sci. Quart.* **4**(1) 20–42.

Kasperson, C. J. 1978. An analysis of the relationship between information sources and creativity in scientists and engineers. *Human Comm. Res.* **4**(2) 113–119.

Kogut, B., U. Zander. 1992. Knowledge of the firm, combinative capabilities, and the replication of technology. *Organ. Sci.* **3**(3) 383–397.

Kuhn, T. S. 1970. *The Structure of Scientific Revolutions*. 2nd ed. International encyclopedia of unified science. Foundations of the unity of science, vol. 2, no. 2, University of Chicago Press, Chicago.

Kulakowski, E. C., L. U. Chronister. 2006. *Research administration and management*. Jones and Bartlett, Sudbury, Mass. ; London.

Lave, J., E. Wenger. 1991. *Situated learning : legitimate peripheral participation*. Cambridge University Press, Cambridge.

Lawrence, P. R., J. W. Lorsch. 1967. *Organization and Environment; Managing Differentiation and Integration*. Division of Research Graduate School of Business Administration Harvard University, Boston.

March, J. G. 1991. Exploration and exploitation in organizational learning. *Organ. Sci.* **2**(1) 71–87.

Merton, R. K. 1957. *Social theory and social structure*. revised & enlarged ed. ed. The Free Press, Glencoe.

Merton, R. K., E. G. Barber. 2004. *The travels and adventures of serendipity : a study in sociological semantics and the sociology of science*. Princeton University Press, Princeton, N.J. ; Oxford.

Nagaoka, S., M. Igami, J. P. Walsh, T. Ijichi. 2011. Knowledge Creation Process in Science: Key Comparative Findings from the Hitotsubashi-NISTEP- Georgia Tech Scientists' Survey in Japan and the US. *IIR Working Paper* **No.11-09**.

Pelled, L. H., K. M. Eisenhardt, K. R. Xin. 1999. Exploring the black box: An analysis of work group diversity, conflict and performance. *Admin. Sci. Quart.* **44**(1) 1–28.

Pelz, D. C., F. M. Andrews. 1966. *Scientists in organizations: productive climates for research and development*. John Wiley & Sons, New York.

Perrow, C. 1967. A framework for the comparative analysis of organizations. *Amer. Sociol. Rev.* **32**(2) 194–208.

Polanyi, M. 1962. The republic of science. *Minerva* **1**(1) 54–74.

Polanyi, M. 1967. *The tacit dimension*. Routldge & Kegan Paul, London.

Powell, W. W., K. W. Koput, L. Smith-Doerr. 1996. Interorganizational collaboration and the locus of innovation: Networks of learning in biotechnology. *Admin. Sci. Quart.* **41**(1) 116–145.

Presser, S. 1980. Collaboration and the quality of research. *Social Stud. of Sci.* **10**(1) 96–101.

Roberts, R. M. 1989. *Serendipity : accidental discoveries in science*. Wiley.

S., Jasjit, Lee F. 2010. Lone inventors as sources of breakthroughs: Myth or reality? *Management Sci.* **58**(1) 41–56.

Sauer, R. D. 1988. Estimates of the returns to quality and coauthorship in economic academia. *J. Polit. Econom.* **96**(4) 855–866.

Scott, W. R. 1981. *Organizations: rational, natural and open systems*. Prentice-Hall, Englewood Cliffs; London.

Selznick, P. 1949. *TVA and the Grass Roots. A study in the sociology of formal organization*. University of California Press, Berkeley; Los Angeles.

Shapiro, G. 1986. *A Skeleton in the Darkroom: Stories of Serendipity in Science*. 1st ed. Harper & Row, San Francisco.

Simon, H. A. 1976. *Administrative Behavior: A Study of Decision-Making Processes in Administrative Organization*. 3rd ed. Free Press, New York.

Stephan, P. E. 2010. *The Economics of Science*, vol. 1. Elsevier, Amsterdam, 217–273.

Stephan, P. E., S. G. Levin. 1992. *Striking the mother lode in science : the importance of age, place, and time*. Oxford University Press, Oxford.

Svensson, G., G. Wood. 2005. The serendipity of leadership effectiveness in management and business practices. *Management Decision* **43**(7) 1001–1009.

Udwadia, F. E. 1990. Creativity and innovation in oragnizations: Two models and managerial implications. *Tech. Forecasting and Social Change* **38**(1) 65–80.

Van Andel, P. 1992. Serendipity "expect also the unexpected". *Creativity and Innovation Management* **1**(1) 20–32.

White, H. 1980. A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. *Econometrica* **48**(4) pp. 817–838.

Woodward, J. 1965. *Industrial Organization: theory and practice*. Oxford University Press, London.

Wooldridge, J. M. 2010a. Asymptotic properties of weighted m-estimators for standard stratified samples. *Econometric Theory* **17**(02) 451–470.

Wooldridge, J. M. 2010b. *Econometric analysis of cross section and panel data*. 2nd ed. MIT Press, Cambridge.

Wuchty, S., B. F. Jones, B. Uzzi. 2007. The increasing dominance of teams in production of knowldge. *Science* **316**(5827) 1036–1039.

Zuckerman, H. 1977. *Scientific Elite : Nobel Laureates in the United States*. Free Press, New York.