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An analysis of the critical role of public science in innovation: the case of biotechnology

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Abstract

Recent studies have found that the overall US industrial base relies heavily on public science, i.e., knowledge that originates from universities, research institutions, government laboratories, etc. This research effort narrows the focus to examine the public science linkage for an important, relatively new industry: biotechnology. Our results indicate that the biotechnology industry depends on public science much more heavily than other industries. In addition, we found that biotechnology companies rely on public science for very basic scientific research, that there is a strong national bias in the citation patterns, and that biotechnology firms rely on science to a much greater extent than large, diversified pharmaceutical companies do.

Keywords: Biotechnology; Public science; Innovation; Patenting; Science references

1. Introduction

Much has been written in recent years about how much organizations depend on external knowledge to enhance their internal innovation efforts. Most of these studies center on 'absorptive capacity' model of Cohen and Levinthal (1990) as a critical component of this process. Cohen and Levinthal define absorptive capacity as the ability of a firm to recognize new information, assimilate it, and apply it to commercial ends. In addition, they argue that a company's innovation processes are comprised of both internal and external elements; therefore, the exploitation of basic scientific discoveries requires an organization to continuously learn from beyond its boundaries.

Recent research (Narin et al., 1997) has shown that, for US industry, relying on external sources of knowledge centers on public science. Public science is defined as scientific research performed in and supported by governmental, academic and charitable research institutions. Narin et al. found that during 1993–1994, 73% of the scientific papers cited by US industrial patents were from public science sources, while only 27% were authored by industrial scientists. Clearly, this finding is strong evidence for the

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continued support of basic research by the various public organizations.

The purpose of this current research effort is to narrow the focus of this analysis to a smaller yet very important section of the US economy: the biotechnology industry. Biotechnology is a new industry that is knowledge-based and predominantly composed of new small firms with close ties to university scientists (Audretsch and Stephan, 1996). More importantly, recent research has found that biotechnology companies play a key role in transferring knowledge from university laboratories to the marketplace. The sixth annual licensing survey by the Association of University Technology Managers estimated that sales of products developed from inventions produced by academic research and licensed to industry amounted to US$20.6 billion in 1996, and that nearly two-thirds of these licenses were to small firms, including biotechnology companies. Thus, from their genesis in academic institutions to their current capacity in licensing ventures, biotechnology companies are critical in commercializing the benefits of academic research, and although the above survey illustrates how much biotechs depend on academic institutions for their licensing products, no research project has quantitatively analyzed how much they depend on public science for their own inventions; it is in this area we seek to make a contribution.

2. A brief history of biotechnology

Although biotechnology in the form of the crossbreeding of animals and the development of hybrid plants has existed for many years, the biotech revolution that this study examines began in 1973. In that year, Stanley Cohen of Stanford and Herbert Boyer of University of California-San Francisco discovered the basic technique for recombinant DNA, which became the basis for genetic engineering (Cohen et al., 1973). New companies followed quickly with some forming as early as 1975 and 1976 (Zucker and Darby, 1997a,b).

Recent research (Patel and Pavitt, 1991; Patel, 1995) has focused on the localized nature of technology production. Both efforts found that large manufacturing firms focused their technological efforts in their home countries, leading to a case of 'non-globalization' of technology. Interestingly, the biotechnology industry is even narrower geographically. The development of biotechnology companies was centered around prestigious universities, primarily in the Boston and San Francisco areas, as other research scientists saw the tremendous personal financial success that the biotech industry offered. Many multi-millionaires have been created when their start-up biotech companies have gone public. Today, over one-third of the public biotechnology companies are in either the San Francisco Bay Area or New England (Ernst and Young, 1998).

Even with the tremendous growth in US biotech (1274 public and private companies in 1998) and the millions made by investors and scientists, it is still somewhat unclear exactly what biotech's contribution to the worldwide pharmaceutical industry will be. According to Zucker and Darby (1997a), the bioscience revolution is not complete, however, biotech is certainly making an accelerating contribution in the production of biological agents and methods to evaluate different compounds. However, returning to the 1998 Ernst and Young Biotechnology Industry Annual Report, there are approximately 2200 biotechnology products currently in development, with 234 pending approval, suggesting as the report says that ''the pipeline has never been more robust'' (p. 10). This is one of the most important reasons that biotech continues to be an important industry to analyze and examine.

There have been a number of studies of the biotechnology industry with some surprising, and some not so surprising, findings. Deeds et al. (1997) found that the publication record of a biotech's scientific team and the firm's physical location were positively correlated with the amount of capital the company could raise in its initial public offering (IPO). Zucker and Darby (1996) showed the critical role of 'star' scientists in when and where biotech companies appeared, and how successful those companies became. Also, confirming Patel and Pavitt (1991), they found that much of the intellectual scientific base for biotechnology is located in California and the Boston area. These geographic issues and relationships in the biotechnology industry were also examined by Audretsch and Stephan (1996).

They found that geographic proximity was important in the university–biotech relationship, even with e-mail, faxes and other electronic communications, and that the specific role played by the university scientist dictated the geographic necessities.

Liebeskind et al. (1996) explored biotech companies from a social network perspective. They uncovered that companies who engaged in joint research and publishing with academic institutions were more effective at sourcing new scientific knowledge than those who did not have joint activities. In short, being part of the social network was important.

And finally, Zucker and Darby (1997a; b) explored how an incumbent pharmaceutical firm adopted a biotechnology approach (drug design vs. random testing) in its research and development efforts. Some other biotechnology 'characteristics' the pharmaceutical company was exhibiting included a movement to encourage more publication, more professor–firm collaborations and numerous collaborations with new biotechnology companies in lieu of other large incumbent firms.

3. The role of public science in innovation

Kenneth Arrow, in his 1962 article concerning the economics of information, discussed the properties of knowledge that make it a public good. These properties include: it is not depleted when shared, once it is made public others cannot easily be excluded from its use, and the incremental cost of an additional user is nearly zero. More recently, there have been sequels to Griliches (1990) seminal analysis that quantified the economic spillovers or unappropriated social benefits that might accrue to society at large from public science-based innovation (Dasgupta and David, 1994). However, though the value of public science has seldom been questioned, its characteristics and properties as well as the appropriate amount to be supplied has received considerable attention of late.

A fundamental premise of economic theory is that competitive markets provide poor incentives for the production of public goods, mainly because the providers cannot appropriate the economic benefits to their creation. However, this explication assumes only a market-based reward structure. Recently, sociologists have extended the market-based approach into a model that illustrates the non-market incentives for scientists to engage in socially responsible activity (Dasgupta and David, 1994; Audretsch and Stephan, 1996).

Much of these non-market incentives focus on the issue of priority and emanate from the writings of Merton (1973). Merton argued that the goal of scientists is to establish priority of discovery by being first to announce an advance in knowledge and that the rewards to priority are the recognition awarded by the scientific community for being first. Thus, scientists should engage in a norm of openness (disclosure) with information, fuelling an ever-expanding body of public science.

More recent research (Dasgupta and David, 1994) extended the Mertonian arguments to include insights from such analytical literature as agency theory and optimal contract as well as the dynamics of racing and waiting games. Their analysis illustrates that the collegiate reputation-based reward system functions rather well in satisfying the requirement of social efficiency in increasing the stock of reliable knowledge, which supports the Mertonian view. However, a more fine-grained analysis they conducted suggests that the unending quest for priority may cause inefficiencies in the allocation of basic vs. applied resources. More importantly, Dasgupta and David could uncover no economic forces that automatically operate to maintain the efficiency of knowledge transfers from university-based open science and commercial science. Part of this inefficiency emanates from the constant friction between academic institutions who desire publication and the establishment of priority, and corporate research sponsors who wish to defer disclosure until appropriate mechanisms (i.e., patents, etc.) can be employed to protect the future economic returns of an innovation. [1]

[1] However, though many companies bemoan the 'academic' approach to research, they report that they rely on it quite heavily. Mansfield (1998) found that drug and medical product companies' reliance on academic research went from 27% of their new products in the 1975–1985 period to 31% in 1986–1994.

Numerous authors have asserted that private firms should invest in basic research (either directly or through sponsorship of academic efforts) even though the economic returns to those investments may not be protected (Rosenberg, 1990; Cohen and Levinthal, 1990). Interestingly, Liebeskind et al. (1996) recently argued that the social norms of science, including the emphasis on priority, may actually provide more protection to innovations than legal methods such as patenting and trade secrets. Yet, these arguments for private research in no way diminish the need and demand for public science, and in fact they suggest that companies should engage in their own research to make better use of the publicly available knowledge. Thus, we set out to explore the reliance on public knowledge that exists in the biotechnology industry.

4. Methodology

As part of another research effort, we requested the IPO prospectuses of the 220 US biotechnology companies that were public traded as of 1993; 119 responded and formed our sample. Our examination of their reliance on public science began with the date of their IPO through 1997, i.e., all patents they acquired since going public. Of course, by using this demarcation in general the longer a company had been public, the more patents it had.

There were two reasons for our approach. First, most previous research on biotechs focused on their pre-IPO links to universities, geographic areas, and even individual scientists (Zucker et al., 1995; Audretsch and Stephan, 1996). Yet, little has been done regarding post-IPO analysis. In essence, the previous research around the public science issue ended at the IPO. Second (and this was clearly a very practical reason), most of the biotechs had few pre-IPO patents, which we found somewhat surprising. Thus, we were limited to patents that had been granted post-IPO. The 119 companies in our sample were granted 2334 patents from their respective IPO dates through 1997; some of the larger ones were Chiron (408 since 1982), Mycogen (138 since 1986) and Genetic Institute (123 since 1986).

In our sample, the total number of patent-to-patent references was 10,335, of which 841 cited patents originated at public institutions (see Figs. 1 and 2 for distributions of the total patent-to-patent references). In addition to the patent references, on each US patent's front page a number of non-patent references (NPRs) are listed as 'other references cited.' NPRs, as they appear on the front pages of US patents, are references to scientific journal papers, meetings, books, technical disclosures and many other types of published material. Our research effort focused solely on scientific journal papers, and more specifically, those that could be matched to papers

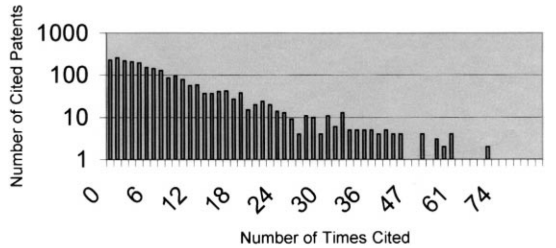

Fig. 2. Distribution of patent citations from the biotechnology patent set.

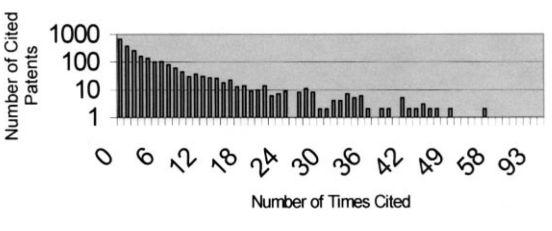

Fig. 1. Distribution of patent citations to the biotechnology patent set.

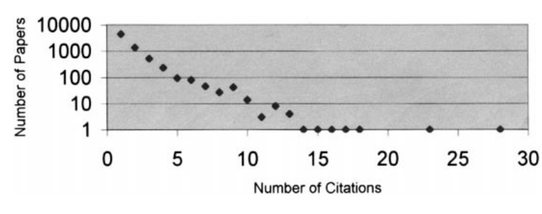

Fig. 3. Distributions of citations per paper for papers cited in the biotechnology patent set.

Table 1
Reliance of biotechnology on US public science: citation distribution to US authors and papers

Author institution type	Citations to institution type	Percentage of total
Public	8568	71.6%
Private	1971	16.5%
Public and private	1422	11.9%
Total	11,961	100.0%

published in the 4000 or so journals covered by the Science Citation Index (SCI) (Fig. 3). [2]

5. Results

Our 2334 biotechnology patents had 23,286 NPRs on their front pages (patent/non-patent reference ratio of 10,335/23,286 or 44.38%), which yielded 20,752 science citations representing 12,477 scientific papers (papers could be cited more than once). Of these citations, we were not able to classify 2745 (13%), usually because a reference might be incomplete, an author's name misspelled, or a wrong volume or page number given. The remaining 18,007 citations were matched with the SCI-based Science Literature Indicators Database (SLID) maintained at CHI Research for the National Science Foundation. For papers with at least one US author, the SLID includes author address information; for our sample, 11,961 citations met this criterion. An analysis of these citations found that 8568 (71.6%) were to papers originating solely at public science institutions (universities, medical schools, research institutes), 1422 (11.9%) cited joint efforts by public and private institutions, and only 1971 (16.5%) cited papers emanating entirely from private companies (see Table 1; Fig. 4). These findings indicate that the biotechnology industry is even more public science linked than other industries. Even compared to only drugs and medicine patents, the biotechnology industry is slightly more public science linked. In their 1997 study, Narin et al. determined that of the US papers cited, drug and medicine patents cited public science 79% of the time.

The next level of analysis was to determine the degree to whether the cited public science research was more basic or more applied. Much research has been done on the role public science plays in basic scientific research (Arrow, 1962; Nelson, 1990). It is commonly assumed that public science organizations are conducting basic scientific research while private companies are engaged in more applied efforts. Yet, part of Cohen and Levinthal's absorptive capacity model assumes that companies, particularly high-tech ones, need an internal basic research ability to effectively leverage public science. Though it is beyond the scope of this paper to examine this phenomenon, the potential desirability of this internal capability is highlighted by the following findings.

The National Science Foundation and CHI Research of Haddon Heights, NJ jointly developed a classification scheme for the journals covered by the SCI (Pinski and Narin, 1976; Narin et al., 1976).

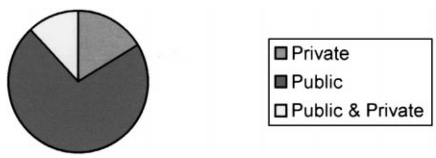

Fig. 4. Institutional source of cited US science references.

[2] An anonymous reviewer correctly highlighted that prior art references can originate from either the applicant or the examiner, and that examiner-based background 'noise' should be examined separately. This issue is quite complicated to address since information regarding applicant vs. examiner sourcing is not provided on the front page of patents. Two studies of which we are aware have explored this issue. Carpenter and Narin (1982) examined 399 prostaglandin patents and found that 94% of the science references originated with the applicant. Collins and Wyatt (1988) studied genetics patents and found that 65% of the science references were from the applicant. They argue that though examiners may use the same set of citations by rote, and that some citations are included to demonstrate the examiner's diligence in searching, ''these difficulties, singly or together, are not so grave as to invalidate the thesis that papers cited in patents, by examiners or by applicants, are to a considerable extent directly and positively relevant to those patents'' (p. 67). More directly related to our study, we explored (thanks to the suggestion of another anonymous reviewer) the distribution of the citations per paper. We found that only seven individual papers were cited more than 13 times each, and that the most frequently cited paper was only cited 28 times out of over 11,000 citations (see Fig. 3). This finding would seem to ameliorate any significant concern regarding either background 'noise' or 'boilerplate' citation patterns.

Table 2
Field of journals where US authored papers appeared

Field	Number of papers	Percentage
Biomedical research	3975	57.8%
Clinical medical	2268	33.1%
Chemistry	402	5.8%
Biology	189	2.7%
Engineering	31	0.4%
Physics	11	0.1%
All others	8	0.1%
Total	6884	100.0%

Their classification scale ranges from 1 to 4 with 1 being the most applied research journal and 4 being the most basic. Our base of 11,961 science references that we classified appeared in 6884 different papers (some papers were cited in more than one patent). Of these, 3975 appeared in biomedical research journals and 2268 were in clinical medicine journals (see Table 2). In addition, of the 6884, 4432 (64%) were in level 4 journals, the most basic research outlets, and 1749 (25%) appeared in level 3 journals (see Table 3). By comparison, of all 1994 US papers published in either biomedical research or clinical medicine, only 37 and 24% were in levels 4 and 3 journals, respectively. Thus, our findings highlight the degree to which biotechnology firms rely on very basic research, and may indicate their need for a continued internal capability to evaluate these external sources.

The importance of public science to commercial biotechnology is demonstrated further by the involvement of prestigious universities and laboratories in the cited papers. For example, as illustrated in Table 4, Harvard University (located in a biotechnology hotbed, Boston) was one of the author affiliations mentioned in 510 cited articles. In addition, the Silicon Valley-based University of California-San Francisco and Stanford University ranked third and fifth in total number of cited papers. This finding is quite consistent with the 'localized' predictions of Patel and Pavitt (1991) and Patel (1995). Finally, it is no surprise that the National Cancer Institute (NCI) tops the list as the NCI has a very large intramural research program.

Table 3
Level of journals where US authored papers appeared

Level of journal	Number of papers	Percentage
Unknown	12	0.3%
1	150	2.1%
2	541	7.9%
3	1749	25.4%
4	4432	64.3%
Total	6884	100.0%

Level 1 is most applied, level 4 is most basic. A few cited journals did not have level assignments.

Table 4
Top 10 identified US author institutions

Institution names	Number of papers
National Institutes of Health (Total)[a]	646
Harvard University	510
National Cancer Institute[a]	296
UC-San Francisco	208
Stanford University	181
US Veterans Administration	177
University of Washington	163
Massachusetts Institute of Technology	163
National Institutes of Health (unspecified)[a]	137
Massachusetts General Hospital	127

[a] The top figure includes the papers for the top 10 locations of the National Institutes of Health. This 646 includes the 296 from the National Cancer Institute and the 137 from the National Institutes of Health (unspecified), as well as eight others.

Table 5
Top 10 identified funding sources for US authored papers

Funding source	Total number of acknowledgments
National Cancer Institute	1127
National Institute of General Medicine Sciences	669
National Institute of Allergy and Infectious Diseases	594
National Heart, Lung and Blood Institute	500
American Cancer Society	321
National Institute of Arthritis and Musculoskeletal Skin Diseases	270
National Science Foundation	269
American Heart Association	138
National Center for Research Resources	123
US Universities and Medical Schools (internally supported)	118

Having determined that public science clearly plays a critical role in the biotechnology field, we set out to determine the funding sources for this 'public science.' As part of a larger research project, involving a search of Philadelphia-area libraries for the research papers published in 1987–1988 and 1993–1994, 3833 US authored papers were examined for funding source acknowledgments. These papers acknowledged over 70 different sources of external support. As described in Table 5, the top two funding sources identified were the NCI and National Institute of General Medicine Sciences with 1127 and 669 acknowledgments, respectively.

Next, we explored the country of origin for the cited papers. Previous research (Narin et al., 1997) uncovered a very strong national bias in the citation patterns for industrial patents. For example, Japanese companies' patents cite Japanese papers three times as often as expected after adjusting for the size of the Japanese publication base. This result was not surprising, but had not been previously tested. Our research effort also confirmed a very strong national bias in the US biotechnology industry. Of the 13,192 total citations (including 1231 without a US author), 64% (8415) were of US origin; the next highest country of origin was the United Kingdom at 7% while Japan was the country of origin for 5% of the papers (see Fig. 5). These results suggest that the national bias is stronger in biotechnology than in the overall US industrial base, possibly due to biotechnology's genesis and continued growth being predominately a US-oriented phenomenon.

Our final analysis compares the linkage to science, and more specifically to public science, of our sample of dedicated biotechnology firms (DBFs) and a group of diversified companies (DCs), in an effort to explore differences between the two. We determined it would be inappropriate to compare the DBFs with all DCs, so we instead focused on the large pharmaceutical companies (see Table 6). Interestingly, the DBFs are much higher in the overall science linkage (i.e., number of science references on the front page of their patents), but the percentage of the two groups' science references that originate in public science are very similar. Nevertheless, it seems clear that one reason DCs may act as bottlenecks in the product development process (between themselves and the biotechnology companies) is that they rely less on science than the biotechnology companies do.

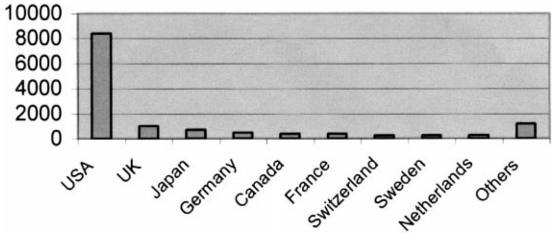

Fig. 5. Country of origin of cited science.

Table 6
Comparison of diversified firms (DFs) and DBFs

	Pharmaceutical companies	DBFs
Science linkage—number of science references	5.8[a]	13.8[a]
Percent of science references originating in public science	79.1%[b]	83.5%

[a] From CHI Research's Tech-line Group Scoreboard for the 5 years ending 1997.
[b] From Narin et al. (1997).

6. Conclusions and implications

We believe that our research findings are important for a number of reasons. First, they confirm the previous findings of Narin et al. that public science plays a very important role in US industry. In fact, our results indicate that the biotechnology industry is even more reliant on public science, and more specifically, basic public science than the pharmaceutical industry. These findings provide strong support for continued public support of basic research, and since biotechnology is widely viewed as having the potential to revolutionize not only the pharmaceutical industry but also the chemical and agricultural industries, this public funding is strategically important to the US economy.

Second, our findings highlight the potential benefits of the Cohen and Levinthal model of absorptive capacity and the need for an internal capability to evaluate external knowledge. Future research should examine the internal capabilities and competencies of biotechnology companies who clearly rely a great deal on external knowledge as part of their innovation processes.

Finally, our results reinforce the findings of Patel and Pavitt (1991) and Patel (1995) concerning the localization of the production of technology. Though this finding was not unexpected, it offers an opportunity for further research on how knowledge is transferred from a university setting to a private firm, and given that companies are increasingly relying on university alliances for their basic research, this area holds much promise for continued study.

Acknowledgements

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References

Arrow, K. 1962. Economics of welfare and the allocation of resources for invention. In: National Bureau of Economic Research, The Rate and Direction of Inventive Activity. Princeton Univ. Press, Princeton, NJ.

Audretsch, D.B., Stephan, P., 1996. Company–scientist locational linkages: the case of biotechnology. American Economic Review 86, 641–652.

Carpenter, M.P., Narin, F. 1982. Assessment of the linkages between patents and fundamental research. Presentation at the OECD Patents and Innovation Statistics Seminar, Paris, France.

Cohen, W.M., Levinthal, D.A., 1990. Absorptive capacity: a new perspective on learning and innovation. Administrative Science Quarterly 35, 128–152.

Cohen, S., Chang, A., Boyer, H., Helling, R., 1973. Construction of biologically functional bacterial plasmids in vitro. Proceedings National Academy of Science 70, 3240–3244.

Collins, P., Wyatt, S., 1988. Citations in patents to the basic research literature. Research Policy 17, 65–74.

Dasgupta, P., David, P., 1994. Toward a new economics of science. Research Policy 23, 487–521.

Deeds, D., DeCarolis, D., Coombs, J., 1997. The impact of firm specific capabilities on the amount of capital raise in an initial public offering: evidence from the biotechnology industry. Journal of Business Venturing 12, 165–187.

Ernst and Young LLP, 1998. New Directions 98: The Twelfth Biotechnology Industry Annual Report. Ernst and Young LLP, Palo Alto, CA.

Griliches, Z., 1990. Patent statistics as economic indicators: a survey. Journal of Economic Literature 28, 1661–1707.

Liebeskind, J., Oliver, A., Zucker, L., Brewer, M., 1996. Social networks, learning, and flexibility: sourcing scientific knowledge in new biotechnology firms. Organization Science 3, 783–831.

Mansfield, E., 1998. Academic research and industrial innovation: an update of empirical findings. Research Policy 26, 773–776.

Merton, R.K. 1973. In: N.W. Storer (Ed.), The Sociology of Science: Theoretical and Empirical Investigations. University of Chicago Press, Chicago, IL.

Narin, F., Pinski, G., Gee, H., 1976. Structure of the biomedical literature. Journal of the American Society for Information Science 27, 25–45.

Narin, F., Hamilton, K., Olivastro, D., 1997. The increasing linkage between US technology and public science. Research Policy 26, 317–330.

Nelson, R.R., 1990. Capitalism as an engine of progress. Research Policy 19, 193–214.

Patel, P., 1995. Localised production of technology for global markets. Cambridge Journal of Economics 19, 141–153.

Patel, P., Pavitt, K. 1991. Large firms in the production of the world's technology: an important case of non-globalisation. Journal of International Business Studies, Fall quarter, 1–21.

Pinski, G., Narin, F., 1976. Citation influence for journal aggregates of scientific publications: theory, with application to the literature of physics. Information Processing and Management 12, 297–312.

Rosenberg, N., 1990. Why do firms do basic research with their own money?. Research Policy 19, 165–174.

Zucker, L.G., Darby, M.R., 1996. Costly information: firm transformation, exit, or persistent failure. American Behavioral Scientist 39, 959–974.

Zucker, L.G., Darby, M.R., 1997a. Present at the biotechnological revolution: transformation of technological identity for a large incumbent pharmaceutical firm. Research Policy 26, 429–446.

Zucker, L.G., Darby, M.R., 1997b. Individual action and the demand for institutions. American Behavioral Scientist 40, 502–513.

Zucker, L.G., Darby, M.R., Armstrong, J., 1995. Intellectual capital and the firm: the technology of geographically localized knowledge spillovers. National Bureau of Economic Research, Working Paper No. 4946, Cambridge, MA.