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Tacit knowledge, localization push, and diffusion of science: Evidence from Singapore

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Abstract

We propose localization push, as an alternative to tacit knowledge, to explain the localization of knowledge diffusion. Sponsors of scientific research enact policies and create institutions for locally-produced knowledge spillovers. We hypothesize that localization necessitated by tacit knowledge renders the local diffusion of such knowledge more productive than distant commercialization. However, this is not the case when the localization push is the primary reason for the localization. We empirically investigate the hypothesis using data on knowledge diffusion in SingaporeOur main findings are as follows: (1) The diffusion of basic research, measured by journal articles cited in patents, is localized, but this is almost exclusively accounted for by Singaporean public institutions; (2) Local patents citing papers authored by Singaporeans are less significant than foreign patents citing such papers; and (3) Singaporean public patent applicants are more willing to seek multijurisdiction patent protection despite the ineffectiveness of their commercialization efforts.

Key words: tacit knowledge; basic research; localization; knowledge diffusion; Singapore

1. Introduction

Basic scientific discoveries are usually non-rival and non-excludable, and thus benefit a broad swath of the economy and society (Arrow 1962). They are generally not patentable and normally placed in the public domain. For these reasons, it becomes difficult for private parties to appropriate returns to investment in basic scientific research, thus making public funding imperative to sustain basic research. A question that then arises is the extent to which the benefits of basic scientific research should be localized to justify public spending. This question is relevant at both the sub-national and national levels. In large countries such as China and the USA, sub-national governments typically fund basic research. The mobility of goods and people across regions diffuses the benefits of basic research conducted in a region. Small open economies such as Singapore may find it difficult to keep the benefits of basic research from crossing national borders.

A large volume of the literature documenting the localization of knowledge spillovers[1] militates against the public good view of basic research. At least some of the benefits of basic research are considered localized for two reasons. First, for developing the basic research findings into practical devices or processes, we need the knowledge or knowhow that is not part of the codified knowledge presented and published in the form of basic research. Such tacit knowledge may remain only with those responsible for the original

basic research, and this creates a natural excludability for basic research. We thus believe that the commercial exploitation of basic scientific discoveries will be located near those responsible for them so that tacit knowledge can be an effective input for the commercialization process. Zucker et al. (1998) finds the colocation of the US biotechnology industry and star scientists working in recombinant DNA corroborating the tacit knowledge hypothesis for the localization of basic research.

The second reason behind the empirical findings of the localization of knowledge diffusion relates to the policies and institutions introduced to keep the benefits of basic research within the local economy. National and regional policy makers have placed great emphasis on fostering the linkages between state, industry, and academia—what Etzkowitz and Leydesdorff (2000) called the 'triple helix'—with the objective of increasing the incidence and intensity of knowledge diffusion from the academia to industry. For example, Belenzon and Schankerman (2013) found that knowledge spillovers from American universities tend to concentrate within state borders and that this is stronger in states adopting policies and institutions for the promotion of knowledge diffusion.

The development of high-tech industries in Singapore is a classic case of the triple-helix approach to technology development and upgrade. In order to launch a then non-existent biomedical industry, from the late 1990s, the government of Singapore provided

incentives for multinational biopharmaceutical companies to locate their R&D and manufacturing facilities in Singapore, nudging local public research institutions to hire top scientists from around the world and local universities to raise their research profile and become entrepreneurial. The linkages between the sectors were part of the concerted efforts (Wong 2007; Hang et al. 2016).

The fact that a localization push can generate localized knowledge diffusion raises questions about the efficiency of local diffusion. Tacit knowledge-driven local diffusion is likely to be more productive since the inputs from those originating the basic research are critical to its effective application. Localized diffusion driven purely by local economic development objectives may result in less effective application when the local economy does not have adequate capacity for the application or tacit knowledge does not provide effective natural excludability. For example, Belenzon and Schankerman (2009) found that American universities adopting strong local economic development objectives tend to be biased toward local companies in licensing university-generated technologies even when it means less revenue.

The literature on localization has largely used the tacit knowledge explanation for localized knowledge diffusion. However, the potentially different outcomes of these two localization approaches have important policy implications. In a large country, the misguided efforts of sub-national governments to promote the local exploitation of locally-conducted basic research can lead to efficiency loss. And, in a small country, this could lead to the promotion of basic scientific research at the expense of inadequate resources for applied research and development. We take the first step to bridge this gap in the literature.

We examine the efficacy of the two mechanisms in Singapore. We measure the commercialization of basic research by the citations made by the US Patent and Trademark Office (USPTO) patents of journal articles, that is, the non-patent literature (NPL) citations. We find the basic research in Singapore more likely to be commercialized by local entities. However, the commercialization of Singapore's basic research tends to be disproportionately undertaken by the public sector, rather than private enterprises, compared to that undertaken by foreign entities. In general, the commercialization carried out locally appears to be less successful than that undertaken by foreign entities when measured by the citations of patents citing basic scientific research. However, we find the opposite result when filing patents in multiple jurisdictions is taken as an indicator of commercialization success: local Singapore public institutions are more likely to file patents in the USA, Europe, and Japan than foreign patent applicants, most of whom are corporate entities.

The rest of the article is organized as follows. The next section relates this study to the literature. Section 3 describes the data construction. Section 4 examines the extent to which the diffusion of basic research conducted in Singapore is localized. Section 5 estimates the impact of the nature of organizations on the significance of their commercialization undertaking. Section 6 concludes the article.

2. Literature and background

2.1 Localized knowledge flows: tacit knowledge vs. localization push

The public good features of knowledge, non-rivalry and non-excludability, make it hard to confine the benefits of such knowledge to its creator. When it comes to basic scientific knowledge, which is usually not eligible for patent protection due to its abstractness, the excludability challenge is even greater. It is perhaps in the best interest of science and humanity that basic scientific knowledge should be a global public good (Stiglitz 1999). However, a legitimate question that the constituents of a nation state can ask is whether their public investment in science benefits the local economy.

What blunts the free flow of knowledge, as implied by the public characteristic of knowledge, is the knowledge component that cannot be easily codified and has to be diffused with the mediation of the creator of such knowledge. This tacitness of knowledge, 'we know more than we can tell' (Polanyi 1958), thus creates a natural excludability for basic scientific knowledge, and roots knowledge, or at least its effective exploitation, to its creator. This is implicit in Marshall's (1920) localized knowledge spillovers hypothesis on agglomeration economies.

The issue of whether knowledge flows are localized or not was not subject to rigorous empirical investigation because the innate mercurial nature of the flow of knowledge made it hard to trace until the publication of the seminal work of Jaffe et al. (1993) (hereinafter *JHT*). On the premise that patent citations trace the flow of knowledge from the cited to the citing patent, they compared the geographical patterns of the local inventors' patent citations with those of the control patents (for the citing patents) sharing the same patent technology class and application year, but not conditional on the patent citation. Their results showed that citations are more likely to be from the same geographical region. JHT interpreted this as evidence of localized knowledge flows. A number of ensuing studies using the USPTO or the European Patent Office (EPO) data largely affirmed this localization finding.[2]

Researchers have attributed the empirical evidence of localized knowledge spillovers to tacit knowledge. Zucker et al. (1998) hypothesized the need of tacit knowledge of star scientists working in the area of recombinant DNA to commercialize their research. They found the star scientists who produced relevant research and the birth and growth of the American biotechnology industry collocated, and interpreted this as evidence that tacit knowledge played an important role in the diffusion of research on recombinant DNA. Using patent citations to trace the flow of knowledge, Almeida and Kogut (1999) found that the mobility of engineers within regional worker networks mediated the knowledge flows for the semiconductor innovations they examined.

In this study, our novel question is whether such evidence of localized knowledge flows indeed indicates strength of the tacit knowledge hypothesis relative to public good hypothesis as regards the diffusion of knowledge. A key motivation for this study is that national and sub-national governments have introduced numerous institutions and policies to catch the benefits of locally-conducted research and development. We call this approach localization push.

The connection between the fundamental scientific research conducted mostly in public research institutions, including academia, and industrial research and development has long been central to public policy deliberations on technology innovation, whether it be in the linear model of basic research leading to applied research and development (Bush 1945) or the Pasteur Quadrant view espoused by Stokes (1997), where scientific research is more often than not motivated by the scientists' desire to create something of immediate use to society as well as their desire to create new knowledge. The Bayh–Dole Act was the first major legislative effort of the USA to influence the orientation of American university research. This act has changed the American universities' attitude towards propertizing and the commercial exploitation of their research (Mowery et al.

2004). The global trend since then has been for university research to increasingly deal with economic development objectives. For example, Japan introduced the Act to Facilitate Technology Transfer from Universities to the Private Sector in 1998, a year after the Japanese version of the Bayh–Dole Act, the Act on Special Measures for Industrial Revitalization, was promulgated. These legislations also aimed to influence the orientation of university research toward serving the purpose of economic development (Japan Patent Office 2016).

The role of scientific research has been prominent in national and regional economic and technology development policy. Etzkowitz and Leydesdorff's (2000) triple helix framework of state, academia, and industry has given scientific research a more explicit and prominent role than the national innovation system approach of Nelson (1993) and Lundvall (1992). Promoting and reinforcing the linkages between state, academia, and industry have been an important objective of regional development policy. Our study is related to Belenzon and Schankerman (2009), who used the citations of patents and scientific papers to investigate how geography and policies and institutions regulate the knowledge spillovers from American universities. They found that distance is a factor for knowledge spillovers but less so when the spillovers are measured by the citations of scientific papers. They also found a significant 'state border' effect: when controlling for distance, knowledge spillovers tend to concentrate within state borders. The state border effect represents the influence of policies and institutions incentivizing within-state licensing of university-generated technologies and regulations restricting worker mobility, and promotes knowledge spillovers.

Numerous regional development policy initiatives are premised on knowledge diffusion benefits from university–industry linkages. For example, regional development agencies in the UK have created various organizations and initiatives, including industrial collaboration centers, and industry-oriented fellowships to promote the collaboration between universities and local industry (Wright 2007). The Ministry of Economy, Trade and Industry of Japan started an 'Industrial Cluster Plan' in 2001. Kodama (2008) described how the local government promoted university–industry collaboration in the Tama region under this plan.[3]

Such policies and institutions designed to promote university–industry linkages contribute to documented evidence on localized knowledge flows based on, for example, patent citations. However, the localization of knowledge flows therein may or may not be driven by the tacitness of knowledge or the technology concerned, but instead may be the result of the local public agencies that fund basic research attempting to keep in the local economy the benefits of the results from their support of research. If the tacitness of knowledge is not critical to the successful exploitation of a new idea or technology, not all localized knowledge flows will lead to higher returns to the exploitation of basic research. If the tacitness of a new knowledge is not significant, then it will be unclear whether a distant party trying to adopt and develop an application for that knowledge is necessarily disadvantaged by her distance from the knowledge creator.

2.2 Basic research and diffusion in Singapore: an example from biomedical science

When Singapore decided to develop its own biopharmaceutical industry, the city state was more or less starting from scratch.[4] The development of this science-based industry proceeded on multiple fronts. A number of well-funded public research institutes were created to conduct cutting-edge research in their respective fields that show translational potential.[5] These research institutes became a platform to attract and retain top scientists, the so-called 'whales', from around the world[6] and responsible for training young scientists and researchers. A number of startups have also spun off over time from these institutes. A biomedical campus was built close to a major local university and its teaching hospital to house these research institutes and industry research laboratories. Bio*One Capital was a state-run venture capital firm created to focus on the biopharmaceutical sector. The local universities were incentivized to become more 'entrepreneurial' and active in serving the technology needs of the local economy (Wong 2007).

From the beginning, public support for basic research in Singapore was driven by the need of the industry to take up higher value-added activities, particularly those of multinational corporations (MNCs) that traditionally played a significant role in bringing investment and generating employment for the local economy. Basic research was a necessary part of the package offered to the big global biopharmaceutical companies to raise the biomedical sector off the ground. One of the early examples of such public–private collaboration was a project jointly funded by then Glaxo of the UK and the Institute of Molecular and Cell Biology of Singapore. The research was conducted at a unit of the research institute, which later spun off as MerLion Pharmaceuticals Pte. Ltd. Over 100 global biomedical sciences companies have set up operations in Singapore since then, as stated by the chairman of the government science and technology agency (Poh 2010).

The linkages between these institutions are important for the system as a whole to function. In translational research, a number of consortia established to promote collaboration between clinicians in the healthcare sector and scientists in the public research institutes and universities helped to set research agenda, coordinate research efforts and resource allocation, connect researchers and research institutes, and provide training.[7]

2.3 Measuring the diffusion of basic scientific research using NPL citations

Patent applicants are required to identify the technology/knowledge on which their inventions are built, or the prior art. The representation of prior art could take the form of other patents (the underlying inventions) or references to NPL, ideas/knowledge presented in technical reports, academic articles, or any type of published material. In American jurisprudence, such references perform the important legal function of delimiting the patent applicants' property right, lending credence to patent citations as a measure of knowledge flow. There are limitations to patent citations as a measure of knowledge diffusion. Not all innovations are patentable; firms may choose secrecy over patents to protect their intellectual property; patent examiners supply a significant portion of patent citations. Despite these confounding noises, as (Jaffe et al. 2020) showed with survey evidence, there remains a significant correlation between patents that inventors cite and the inventors' perception of how economically and technologically important these patents are.

One of the earliest studies of this literature, Collins and Wyatt (1988) examined the basic science paper citations made by 366 genetics patents granted between 1981 and 1985. A main finding of the study is that countries tend to cite their own papers more than others, indicating a home country bias. Also, UK papers attract more patent citations than others, and Japanese patent applicants cite UK papers more than UK applicants do. Studying much larger

samples of the USPTO and EPO patents, Callaert et al. (2006) found that more than one-third of the patents cite non-patent references, more than half of them being journal references.

Tijssen (2002) questioned the validity of non-patent references as indictors of 'technology's science dependence'. On the other hand, Roach and Cohen (2013) matched the patent data to survey data at the research and development lab level to evaluate the validity of patent citations as a measure of knowledge flows from public research. They concluded that 'non-patent references (e.g., journals and conferences), and not the more commonly used patent references, are a better measure of knowledge originating from public research'.

Several recent economic studies have used NPL citations of journal articles as a measure of basic research diffusion. For example, Branstetter and Ogura (2005) used the NPL citations of academic papers to measure the knowledge spillovers from the academia to industry, which they found more in 'bioscience-related' technology fields; Belenzon and Schankerman (2009) used both patent and NPL citations to measure the knowledge diffusion from American universities; and Azoulay et al. (2015) used the journal paper references in patent documents to trace the link between public-funded research (NIH grants) and its commercialization by private industry, measured by the pharmaceutical and biotechnology firm patenting.

3. Data

We obtained the NPL citation data from PATSTAT, a global patent bibliographic database compiled and maintained by the European Patent Office. All the NPL references in all the USPTO patents were extracted and matched with the papers authored by Singaporeans[8] recorded in the Web of Science (WOS) database. This process identified 6,219 science and technology papers authored by Singapore researchers and cited by USPTO patents.[9] We retained only the patent applicants supplied NPL citations and those patents that listed at least one non-individual assignee for our analysis. The appendix gives a detailed description of the algorithm used for identifying the NPL references and their matching to the WOS bibliographic information.

Two-thirds of the cited articles are authored by Singaporean researchers only; that is, all the listed authors' addresses are in Singapore. Table 1 tabulates the highly skewed distribution of the number of times the papers were cited by USPTO patents. Most of them have been cited only once, and one-third of them were cited two to five times. Only 10 per cent of the papers were cited more than five times, with less than half a percent of them cited more than fifty times. The distribution of citation counts is similar for papers authored by Singapore authors only and those involving foreign co-authors.

Of the 14,392 USPTO patents citing papers authored by Singaporeans, around 400 involved a Singapore applicant or inventor. Table 2 shows the distribution of patents by technology field. The distribution is similar for Singapore and foreign patents, with about 80 per cent of patents coming from chemistry and electrical engineering fields. Chemistry covers technologies such as biotechnology and pharmaceuticals, while electrical engineering includes computer technology and semiconductors.

Table 3 reveals sharp differences between foreign and Singapore patents in assignee type. Non-corporate applicants such as public institutions, universities, and hospitals account for 75 per cent of Singapore patents, but their share in foreign patents is only about 20

Table 1. Distribution of NPL cite counts for cited S&T papers.

Number of NPL cites	Singapore author only		International collaboration	
	Number	%	Number	%
1	2,347	57.8	1,185	55
2–5	1,340	33.0	728	33.8
6–10	213	5.2	139	6.4
11–20	105	2.6	60	2.8
21–50	53	1.3	36	1.7
>50	3	0.1	8	0.4
Total	4,063	100.0	2,156	100

Table 2. Distribution of patents citing S&T papers by technology sector.

Tech sector	Foreign		Singapore	
	Number	%	Number	%
Chemistry	4,306	30.8	175	42.5
Electrical engineering	6,972	49.9	161	39.1
Instruments	2,229	16.0	55	13.3
Mechanical engineering	342	2.4	20	4.9
Other fields	120	0.9	1	0.2
Total	13,969	100.0	412	100.0

per cent. Most of Singapore's domestic commercialization of basic research is driven by public institutions, whereas the opposite is true with foreign patents; the vast majority of foreign commercialization of basic research conducted in Singapore is done by the corporate sector.

4. Localization of diffusion

We first test whether the diffusion of locally-produced basic research is localized by examining the extent to which papers authored by Singaporeans are disproportionately cited by Singapore patents. Our approach of comparing the share of patents citing Singapore papers that were filed by Singapore applicants conditional on the patent citing Singapore papers with the share obtained from a control sample that is not conditional on the patent citing Singapore papers, is similar to that of JHT.[10] We report the results in Table 4.

The top panel includes self-citations in the computation. The shares of citations matched to Singapore are reported for both the citing and the control samples. Below the two shares is a statistic from a *t*-test of the shares being equal. We conduct the test for the full sample and separately and individually for the three sectors of technology for which we have a sufficient number of observations. The average share of citations, including self-citations, is 5 per cent for the citing versus 0.7 per cent for the control sample. The evidence for localized exploitation of basic research in Singapore is robust, and there is variation by technology sector: chemistry showed the strongest evidence of localization; compared to 8.5 per cent of the citing patents, only 0.3 per cent of the control patents were Singaporean. As regards magnitude, the shares as well as difference between them are much smaller for electrical engineering.

We then exclude self-citations from the computation and report the results in the bottom panel. The shares of local citations in the

Table 3. Distribution of patents citing S&T papers by assignee type.

Assignee type	Foreign		Singapore	
	No.	%	No.	%
Public only	691	4.9	163	39.6
Corporate only	11,280	80.7	84	20.4
University only	1,625	11.6	122	29.6
Corporate + Noncorporate	306	2.2	28	6.8
Public + University	78	0.6	15	3.6
Total	13,980	100.0	412	100.0

Table 4. Localization test: fractions of citations matched to Singapore.

	All	Chemistry	Electrical engineering	Instruments
Including self-cites				
Citing	0.050	0.085	0.026	0.046
Control	0.007	0.003	0.009	0.004
t-statistic	25.031	21.763	8.452	10.104
Number of citations	17,809	5,829	8,634	2,739
Excluding self-cites				
Citing	0.016	0.024	0.012	0.010
Control	0.006	0.004	0.009	0.003
t-statistic	8.107	8.997	1.588	3.293
Number of citations	16,813	5,319	8,349	2,584

Table 5. Localization test by assignee type.

	All	Chemistry	Electrical engineering	Instruments
Public				
Citing	0.051	0.058	0.048	0.028
Control	0.006	0.005	0.01	0.002
t-statistic	10.668	8.679	4.477	3.787
Number of citations	3,064	1,651	768	544
Corporate				
Citing	0.008	0.009	0.008	0.005
Control	0.006	0.003	0.009	0.003
t-statistic	1.286	3.321	−0.696	1
Number of citations	13,749	3,668	7,581	2,040

Note. Public assignees include public research institutes, universities, hospital, etc. Corporate assignees include corporations and corporate–public collaborations.

citing sample drop sharply when only the non-self-citations are counted, but they are still larger than those of the control sample, with the differences statistically significant for all fields but electrical engineering.

Public policy and institutions promoting the local diffusion of basic research are likely to involve public research institutes and universities. If localization push is the primary motive behind the localized diffusion results, then localization should be more prominent among public institutions than corporations. To explore this hypothesis, we separately conduct a localization test for the two types of assignees excluding self-citations. The results are tabulated in Table 5.

When we compare the results for the two types of assignees in the top and bottom panels, respectively, we clearly find that the shares of citations matched to Singapore are much higher for public sector patents than for corporate patents. The overall localization rate of 5.1 per cent for the public sector is over five times higher than that for the corporate sector. The large difference holds for all the three technology fields. There is no evidence of localization for the corporate sector except for chemistry.

A source of bias for the localization test is our definition of localized diffusion, which may not be accurate. For an example, consider a paper co-authored by a Singapore-based researcher and a MIT researcher, and cited by a patent listing the applicants or inventors residing in Boston, MA. Our test would have counted this as nonlocal citations, although it should be counted otherwise. This is because the PATSTAT data do not allow us to pin down the address of each patent applicant or inventor even when all the addresses and country information available are used. To address this concern, we restrict the sample to citations of only papers authored by Singapore authors. The results shown in Table 6 closely resemble our previous report: localized diffusion results are largely driven by public sector patents citing Singapore-authored articles.

In sum, we first establish that the diffusion of the basic research of Singapore researchers occurs disproportionately within the country, predominantly accounted for by public institutions such as public research institutes, public universities, and hospitals. When compared with the findings in the literature, we reaffirm the localized knowledge diffusion results, but with the new insight that such results are driven by public sector efforts in the context of Singapore. Another contrast we find is that the magnitudes of localized diffusion in Singapore are much smaller than what researchers find for a much larger country such as the USA. We find the share of local citations of locally-authored papers at most around 5 per cent, whereas JHT used patent citations to find that 70 per cent of diffusion occurs locally, and Belenzon and Schankerman (2009) found that 9 per cent of knowledge diffusion is captured within 25 miles of the origination of the knowledge when using the academic article citations in patent documents to measure knowledge diffusion.

5. Outcome of diffusion

The public sector-driven local diffusion of basic research raises the question of whether it is as effective as the private or corporate sector-driven local diffusion. The existing literature has stopped short of investigating the potential differences in diffusion efficiency when motivated by different types of entities. We estimate the following equation to investigate the impact of different motivations for the localization of basic research:

$$Y_{ij} = \alpha \text{Singapore}_i + R_i\beta + X_j\gamma + \mu_c + \xi_t + \nu_l + \sigma_{ij} \qquad (1)$$

We take each patent citation of a scientific paper as a commercial exploitation of the basic research contained therein. While it is not an accurate term for what we measure, we refer to this as commercialization for lack of a better word. This commercialization is measured by Y_{ij} for patent i citing paper j. Thus, the estimation observations are couples of i and j. Patent i was from technology sector c with application year t, and paper j was published in year l. The coefficient of key interest is that of *Singapore*, indicating that the citing patent is a Singapore patent; that is, at least one nonindividual applicant has a Singapore address.

The citing patent characteristics collected in R_{ict} include Age (the number of years elapsed since the patent application was filed), Age^2; citation lag (the year the application for patent i was filed

Table 6. Localization test by assignee type: Singapore authors only

	All	Chemistry	Electrical engineering	Instruments
Public				
Citing	0.046	0.055	0.046	0.015
Control	0.008	0.007	0.017	0.000
t-statistic	7.11	5.907	2.663	2.249
Number of citations	1,791	898	477	344
Corporate				
Citing	0.008	0.011	0.008	0.003
Control	0.006	0.003	0.009	0.003
t-statistic	1.2573	3.145	−0.322	0
Number of citations	8,775	1,939	5,141	1,394

Note: Public assignees include public research institutes and universities. Corporate assignees include corporations and corporate–public.

Table 7. Summary statistics.

	Mean	Std. dev.	Min	Median	Max
Forward cites	4.558	11.330	0	1	309
Page rank ($\times 10^6$)	0.055	0.053	0.029	0.038	1.323
Triadic	0.283	0.450	0	0	1
Age	7.857	3.674	1	7	23
Age^2	75.230	65.900	1	49	529
Patent counts	8,454	23,129	0	312	1,52,222
citation lag	5.015	4.432	−17	4	30
Journal impact factor	4.021	7.564	0	2.186	59.560
Patent application year	2007	3.674	1992	2008	2014
Article publication year	2002	4.811	1975	2002	2015
Singapore	0.050	0.219	0	0	1
MNC Singapore	0.013	0.112	0	0	1
All local	0.037	0.190	0	0	1
Corporate foreign	0.755	0.430	0	1	1
Public Singapore	0.041	0.199	0	0	1
Public foreign	0.174	0.379	0	0	1
Corp-public Singapore	0.003	0.053	0	0	1
Corp-public foreign	0.021	0.142	0	0	1

Note: There are a total of 17,809 observations. Each observation is a citing patent-cited article couple.

minus the year the cited paper was published); and log(patent counts), the patent applicant's patent stock in logarithm as of the year of filing the application for the citing patent.

The patent stock is constructed as the weighted sum of the patents that the applicants of patent *i* had applied for by the patent application year, with the weights constructed as the number of forward citations a patent received within five years of its application date. We use the patent stock variable as a proxy for the patent applicant's ability to innovate and successfully commercialize basic scientific research.

For the paper characteristics, we include in X_{jl} the impact factor of the journal in which the cited paper was published. The journal impact factor helps to differentiate the quality of the underlying basic research for the paper. We also control for patent technology sector (μ_c),[11] application year (ξ_t), and paper publication year (ν_l) fixed effects when estimating Equation (1).

We use several indicators to measure the significance of commercialization (Y_{ij}), such as number of forward citations the patent citing a scientific paper has received, a PageRank (PR) index, and an indicator of whether the applications were filed for an invention underlying a paper-citing patent in three jurisdictions, the USA, Europe, and Japan, that is, triadic patents. We present in Table 7 summary statistics for the dependent and independent variables used in the subsequent regression analysis.

5.1 Forward citation counts

We first estimate Equation (1) using the number of forward citations that a patent received as a measure of its technological and economic significance.[12] An obvious concern is the truncation bias: we expect to find more citations for older patents with the passage of time, everything else being equal. We deal with the truncation issue by including the age variables in the regressions: older patents generate more citations, but at a declining rate due to knowledge obsolescence. In the meantime, the patent application and publication year fixed effects account for any unknown time trends in the patent citing behavior and basic research productivity.

We estimate Equation (1) using a Poisson estimator. A potential concern with the Poisson specification is its assumption the mean and variance of the underlying distribution are equal. When this assumption is violated, the standard errors generated by the Poisson model are biased downward, resulting in inflated statistical significance levels.[13] An alternative estimator is the negative binomial estimator, which replaces the equal-mean-variance assumption with

one of a parametric distribution of the mean. We deal with the inconsistent standard error estimates problem by following Wooldridge's (2002) suggestion of computing robust standard errors clustered by, in our case, citing patents. We also estimated a log-linear OLS model where the dependent variable is the logarithm of forward citations. The results are available upon request and are similar to those generated by the Poisson estimator.

The first set of estimates obtained using a Poisson estimator is reported in column (1) of Table 8. Self-citations are included in the estimation. Age and Age^2 have the expected sign, suggesting that both knowledge diffusion and obsolescence rise with the passage of time. The citation lag coefficient estimate implies that a longer time lag between the basic research publication and its commercialization leads to more significant innovation. Neither the applicant's innovation capability measured by her stock of patents nor the impact factor of the journal in which the paper was published has any impact on the significance of commercialization. The standard errors are clustered by patent (*i*).

The coefficient of *Singapore* allows for examining the relative efficacy of the local vs. distant commercialization of basic research in Singapore. The estimate reported in column (1) of Table 8 suggests that such localized diffusion or commercialization of locally-conducted basic research is less effective than the diffusion occurring outside Singapore. Besides, the magnitude of the effect is quite large; local diffusion generates 90 per cent fewer citations than foreign diffusion. The difference between columns (1) and (2) is that self-citations are excluded from the column (2) estimation. Thus, the Singapore coefficient is somewhat reduced in absolute value, suggesting that self-citations represent less effective basic research exploitation than that carried out by an entity not responsible for generating the basic research.

We then split the Singapore–foreign dichotomy into six finer categories: corporate, public, and corporate-public for the Singapore and foreign patents citing Singapore-conducted basic research. Estimates of these group effects are reported in the third column of Table 8. Foreign patents dominate Singapore patents for each of the three assignee types; the worst-performing group in terms of

Table 8. Significance of knowledge diffusion: forward citation count.

	(1) All (+self)	(2) All	(3) All	(4) SG only
Age	0.447**	0.442**	0.443**	0.522
	(0.178)	(0.179)	(0.179)	(1.218)
Age^2	–0.012*	–0.012*	–0.012*	0.045
	(0.007)	(0.007)	(0.007)	(0.146)
citation lag	0.027*	0.028*	0.027*	0.019
	(0.016)	(0.016)	(0.017)	(0.035)
log(patent counts)	–0.004	–0.003	–0.003	–0.002
	(0.006)	(0.006)	(0.006)	(0.007)
log(journal impact factor)	–0.003	–0.004	–0.003	–0.007
	(0.008)	(0.008)	(0.008)	(0.009)
Singapore	–0.907***	–0.724***		
	(0.135)	(0.169)		
Corporate foreign			0.588**	0.608**
			(0.238)	(0.292)
Public Singapore			–0.354	–0.258
			(0.336)	(0.422)
Public foreign			0.486**	0.606**
			(0.245)	(0.300)
Corp.–public Singapore			0.669	–1.239***
			(0.557)	(0.389)
Corp.–public foreign			0.823***	1.024***
			(0.258)	(0.314)
Log-likelihood	–79,233	–76,436	–76,328	–49,505
Observations	17,121	16,169	16,169	10,230

Note: All regressions include patent technology sector, patent application year, and paper publication year fixed effects. Standard errors clustered by patent application ids are reported in parentheses.

*$p < 0.1$,

**$p < 0.05$,

***$p < 0.01$.

generating forward citations is the Singapore joint corporate public group, which consists of patents listing both public and corporate entities as co-applicants.

The difference between columns (3) and (4) is that only papers solely authored by Singaporean researchers are shown in column (4). The reason for this is the same as for the localization test: papers with international collaboration involve foreign researchers, meaning that foreign patents citing such papers may actually represent local diffusion. The results are sharper than those of column (3): foreign commercialization is even more effective than local commercialization, and the coefficients of the three foreign assignee-type variables become even larger. Note that the contrast between the foreign corporate–public group and the Singapore corporate–public group has become much sharper, with the latter being the least effective in commercialization of basic research.

5.2 A PR importance index for patents

A forward citation count assigns equal weight to all the forward citations of a patent. One could argue that the patents cited by more important patents could be more important themselves, everything else being equal. Thus, forward citations by patents that are themselves more important should carry more weight in the computation of forward citation count. This is the approach of Trajtenberg et al. (1997) when they used the sum of the forward citations of a patent and a fractional weight multiplied by the number of citations received by those citing patents to measure the importance of an invention. They

found university patents more important than corporate patents by this measure. This idea can be taken further using Google's PR algorithm (Page et al. 1999) to rank web pages by their relevance to a search query to create an importance index for patents.[14]

We use the following definition to create a PR importance index for patents:

$$\mathrm{PR}(p_i) = \frac{1-d}{N} + d \sum_{p_j \in M(p_i)} \frac{\mathrm{PR}(p_j)}{L(p_j)} \quad (2)$$

where the PR of patent p_i is determined by, among other factors, the total number of patents (N) and parameter d, the damping factor, which is assumed to be 0.85 by convention. The set of patents, $M(p_j)$, collects all the patents citing patent p_i. $L(p_j)$ represents the number of citations made by the patent p_j.

We create the PR index with Equation (2), which turns out to be highly correlated with the naive forward citation count with a correlation coefficient of 0.7. We proceed to estimate Equation (1) using the logarithm of this PR importance index as the dependent variable. Since PR is a ranking index that has only cardinal meaning, the coefficient magnitudes obtained therewith and reported in Table 9 are not directly comparable to those based on the forward citation counts that we just reported. The patterns of results are quite similar to those in Table 8: the Age variables coefficients, although smaller, remain statistically significant and indicate both increasing knowledge diffusion and obsolescence over time. The other control variables remain statistically insignificant. We will next discuss the location variables.

Columns (1) and (2) show that the PR importance index is significantly lower for local commercialization than for foreign commercialization. The patterns of differences by assignee type are similar to those of Table 8: foreign commercialization of papers authored by Singaporeans receives higher PR importance index values than local commercialization for all the three assignee types, corporate, public, and corporate–public. While commercialization by the corporate–public Singapore entities is the least significant with forward citations counts and papers authored by Singaporean researchers only (column 4), the coefficient remains negative when the PR index is used to measure the commercialization success, but it is not statistically significant.

5.3 Triadic patents

Another indicator of commercialization success is whether multijurisdiction applications have been filed for the paper-citing patent. Obtaining patent protection in multiple jurisdictions helps secure the property right of an invention in multiple markets. Higher potential returns from multiple filings also bear costs, including not only the expenses for patent application in each jurisdiction but also those for enforcing them after they are granted. Therefore, filing patent applications in multiple jurisdictions is indicative of higher value of the underlying invention, at least from the patent applicant's perspective, justifying the higher costs of multiple patent filings and the associated enforcement. An alternative measure of significance of the paper-citing patent is whether the patent family contains filings in three jurisdictions, the USA, Europe, and Japan (Helene and Khan 2004). Equation (1) is estimated using a linear probability estimator.[15] The results are reported in Table 10.

The most striking difference between these results and those discussed earlier is with respect to the effectiveness of local diffusion. The results from using both self-citations and non-self-citations (column 1) indicate no difference between the foreign and Singapore

Table 9. Significance of knowledge diffusion: PR index

	(1) All (+self)	(2) All	(3) All	(4) SG only
Age	0.110***	0.111***	0.111***	0.087***
	(0.017)	(0.017)	(0.017)	(0.007)
Age^2	−0.002***	−0.002***	−0.002***	−0.002***
	(0.000)	(0.000)	(0.000)	(0.000)
Citation lag	0.014	0.014	0.014	−0.015***
	(0.016)	(0.016)	(0.016)	(0.001)
log(patent counts)	−0.001	−0.002	−0.002***	−0.002
	(0.001)	(0.001)	(0.001)	(0.002)
log(Journal impact factor)	−0.000	−0.000	−0.001	−0.001
	(0.002)	(0.002)	(0.002)	(0.002)
Singapore	−0.140***	−0.164***		
	(0.029)	(0.034)		
Corporate foreign			0.178***	0.155***
			(0.047)	(0.061)
Public Singapore			0.031	−0.024
			(0.068)	(0.083)
Public foreign			0.197***	0.174***
			(0.049)	(0.064)
Corp-public Singapore			0.032	−0.038
			(0.079)	(0.101)
Corp-public foreign			0.200***	0.179***
			(0.056)	(0.072)
Adjusted R^2	0.278	0.279	0.279	0.294
Observations	17,121	16,169	16,169	10,230

Note: All regressions include patent technology sector, patent application year, and paper publication year fixed effects. Standard errors clustered by patent application ids are reported in parentheses.

*p < 0.1,

**p < 0.05,

***p < 0.01.

Table 10. Significance of knowledge diffusion: triadic patents

	(1) All (+self)	(2) All	(3) All	(4) SG only
Age	0.023***	0.032***	0.035***	0.010
	(0.009)	(0.009)	(0.009)	(0.020)
Age^2	−0.002***	−0.002***	−0.003***	−0.002***
	(0.000)	(0.000)	(0.000)	(0.001)
Citation lag	−0.023***	−0.023***	−0.023***	−0.027***
	(0.003)	(0.003)	(0.003)	(0.001)
log(patent counts)	−0.002*	−0.001	0.000	0.003*
	(0.001)	(0.001)	(0.001)	(0.001)
log(Journal impact factor)	−0.000	−0.001	0.001	0.005***
	(0.001)	(0.002)	(0.001)	(0.002)
Singapore	−0.033	0.130***		
	(0.032)	(0.045)		
Corporate foreign			−0.051	−0.060
			(0.059)	(0.072)
Public Singapore			0.057	0.000
			(0.087)	(0.102)
Public foreign			−0.207***	−0.205***
			(0.060)	(0.073)
Corp-public Singapore			0.316**	0.248
			(0.151)	(0.216)
Corp-public foreign			−0.117*	−0.164*
			(0.065)	(0.080)
Adjusted R^2	0.054	0.057	0.073	0.063
Observations	17,798	16,802	16,802	10,557

Note: All regressions include patent technology sector, patent application year, and paper publication year fixed effects. Standard errors clustered by patent application ids are reported in parentheses.

*p < 0.1,

**p < 0.05,

***p < 0.01.

patents citing papers authored by Singaporeans in terms of being a triadic patent. When the self-citations are omitted from the regression, Singapore patents are 13 per cent more likely to be triadic.

Examining how the results vary by assignee type reveals that Singapore commercialization shows a greater likelihood to seek triadic patent protection because of the higher propensity of the Singapore public and the corporate–public applicants to file triadic patents than their foreign counterparts. Foreign public patent applicants are much less likely to obtain triadic patent protection than foreign corporate patent applicants. There is no such public–corporate distinction for Singapore patent applicants. In fact, the Singapore corporate–public joint applicants are 32 per cent more likely to apply for patents in the three major patent offices than corporate Singapore patent applicants. The difference becomes statistically insignificant only when we concentrate on the scientific papers authored solely by Singaporean researchers.

One reason for the difference in results when using citation-based significance measures and the triadic application status measure is that the latter reflects the patent applicant's expected value of the underlying invention, whereas citations are indicative of the actual and realized performance. Furthermore, the desire for the commercialization of locally-generated basic research may weaken the budget constraint of the Singapore public patent applicants, who file more triadic patent applications than their foreign counterparts.

5.4 Extensions
We extend our baseline analysis by examining the local diffusion of basic research for two particular groups of patent applicants, MNCs

with a base in Singapore[16] and 'indigenous' Singapore institutions; in the latter, none of the applicants or patent inventors has a foreign address. We are interested in the MNCs in Singapore since they have played an instrumental role in its economic and technological development.[17] Serving them with local technical expertise was one of the motivations for the Singapore government's support for local basic scientific research (Hang et al. 2016).

In column (1) of Table 11, we added to the baseline regression (column 2 of Table 8), two indicator variables besides the one indicating whether it is a Singapore patent or not: MNC Singapore and Corporate foreign. The former represents the patents of foreign MNC having a Singapore presence (in the form of an applicant or inventor with Singapore address); the latter includes all foreign (no Singapore address) corporate entities. Therefore, the reference group is non-corporate foreign, and the Singapore indicator now references the non-MNC local Singapore applicants. The underperformance of Singapore's local diffusion of basic research remains, but with the result indicating that it does not apply to those MNCs with at least part of the patent-generating invention carried out in Singapore. However, when we restrict the basic research to Singaporean researchers only, the MNC Singapore group underperforms at least like the local Singapore group (column 2), compared to the foreign commercialization efforts. In other words, the MNC's local exploitation of Singapore-authored basic research is more productive when it is an internationally collaborative effort.

We then consider the case of an all local product patent; that is, all the applicants and inventors are from Singapore. The results are

Table 11. Significance of knowledge diffusion: extensions with forward citation count.

	(1) All (+self)	(2) All	(3) All	(4) SG only
Age	−1.431*	0.475	−1.442*	0.505
	(0.829)	(1.214)	(0.827)	(1.217)
Age^2	0.255**	0.049	0.256**	0.046
	(0.102)	(0.145)	(0.102)	(0.145)
Citation lag	0.026	0.012	0.026	0.012
	(0.029)	(0.036)	(0.029)	(0.036)
log(patent counts)	0.003	0.006	0.002	0.005
	(0.006)	(0.008)	(0.007)	(0.008)
log(Journal impact factor)	0.002	−0.006	0.001	−0.006
	(0.008)	(0.009)	(0.008)	(0.009)
Singapore	−0.655***	−0.735***	−0.308	−0.361
	(0.177)	(0.223)	(0.250)	(0.340)
MNC Singapore	−0.068	−0.984***		
	(0.377)	(0.196)		
Corporate foreign	0.063	−0.033		
	(0.060)	(0.076)		
All local			−0.671**	−0.631
			(0.311)	(0.416)
Log-likelihood	−76,923	−49,436	−76,912	−49,563
Observations	16,169	10,230	16,169	10,230

Note: All regressions include patent technology sector, patent application year, and paper publication year fixed effects. Standard errors clustered by patent application ids are reported in parentheses.

*p <0.1,
**p <0.05,
***p <0.01.

reported in columns (3) and (4). Now, the reference group is 'all foreign'; that is, none of the applicants are from Singapore. 'All local' refers to the indigenous patents as previously discussed; Singapore now stands for all other Singapore patents with foreign applicants. In column (3), the all local group is behind the underperformance of localized diffusion of basic research with its negative and significant coefficient relative to Singapore's insignificant coefficient. When the origin of basic research is restricted to Singapore authors, the effect remains negative and similar in magnitude, but with too few observations for any statistical significance.

6. Summary and concluding remarks

Many studies have examined the extent to which knowledge diffusion is localized. Knowledge, particularly that produced by basic scientific research, embodies the public good features of non-rivalry and non-excludability. This makes it difficult for its sponsors, often the public sector, to reap returns on their investment. The difficulty of capturing the benefits of basic research locally has led to public policies and institutions designed to keep knowledge spillovers local. On the other hand, the tacit knowledge hypothesis suggests that knowledge spillovers will be localized even in the absence of such localization-promoting policies and institutions. The literature has largely used the tacit knowledge hypothesis to rationalize the widely reported evidence of localized knowledge spillovers.

We contribute to this literature by proposing the localization push as another driving force behind the documented evidence of localized knowledge spillovers and investigating the efficiency consequences of the two mechanisms. Our hypothesis is that the two forces behind the localization of knowledge diffusion differ in

efficiency implications. Localized knowledge diffusion necessitated by the tacitness of knowledge that requires geographical proximity makes the resulting exploitation of knowledge more productive than that undertaken by a distant party without access to such tacit know-how. On the other hand, public policies and institutions may increase localization even when the tacit component of the knowledge is absent, leading to no productivity advantage of localized diffusion.

We test this hypothesis taking Singapore for a case study. We consider patents citing journal articles as an indicator of commercial exploitation of basic scientific research. Notwithstanding its limitations, these NPL citations directly connect the creator of basic scientific research and the party that attempts to create an innovation drawing on the basic research. Our results show that the diffusion of basic research conducted in Singapore occurs disproportionately within the country, but is primarily driven by the local public or semi-public institutions.

We then investigate the effectiveness of localized diffusion in relation to that undertaken by a foreign entity. When the forward citations of paper-citing patents are used as a measure of their technological and economic significance, we find Singapore paper citing patents receiving fewer citations than their foreign counterparts, suggesting that localized diffusion may not be as effective as distant diffusion for basic scientific research conducted in Singapore. This is true for all types of assignees; both public and corporate patents taken out by Singapore entities receive fewer citations.

However, when we consider whether a patent is triadic, that is, whether its family contains applications in all the three patent offices of the USPTO, EPO, and Japan

For the Patent Office (JPO) as an indicator of effective diffusion, we obtain the opposite results. Singapore patents are more likely to be triadic than foreign patents, and the results are mostly driven by the differences between Singapore and foreign public institutions. Singapore public institutions are more likely to file patent applications in the three jurisdictions than their foreign counterparts. A potential explanation that merits further investigation is that Singapore public institutions are less concerned about the costs of filing patent applications in multiple jurisdictions and hold a premium on the option value of multijurisdiction patents.

We would like to shed more light on the concrete mechanisms behind our results in future research. For example, what explains the less productive local diffusion of Singapore-authored basic research? How has the role of multinational corporations in local knowledge diffusion evolved over time? These would yield further insights about the policy implications of our research.

We focused on Singapore partly because the size of the city state makes the data construction tractable. It will be interesting to apply this study to a large country, although the data-generating task would multiply exponentially. An important caveat is that our findings should not be interpreted to assess the overall welfare impact of investment in basic research. For example, our analysis does not consider the training of science and engineering students that basic scientific research inevitably produces.

A appendix constructing the NPL-WOS database

We start by extracting all the NPL citations from the US Patent and Trademark Office patents in the PATSTAT database, which yields 27 million NPL records. We also acquire data on 215 thousand articles from the WOS database that list at least one Singapore

author address. We then use two algorithms to match the NPL citation data to the WOS publication data.

1. OECD algorithm

In the first procedure, we use the algorithm developed by researchers from K.U. Leuven and Bocconi University for the OECD (Callaert et al. 2014). For each NPL reference, we search in the population of Singapore-authored publications for potential matches, which are identified by a combination of meta-information (e.g., publication title, publication year, last name of first author, journal title, volume and issue numbers, beginning page). The validity of these potential matches is then further evaluated based on a number of criteria. For example, if a NPL reference contains at least 90 per cent of the strings of the matched WOS title, then it is considered a valid match; otherwise, similarity based on the other indicators is used to compensate for the inaccuracy of the title comparison.

2. Our algorithm

Compared to the OECD algorithm, we perform a reverse procedure: for the title of each Singapore WOS publication, we find the best matching NPL references in the PATSTAT database by using a two-step approach.

> Step 1: *Identify potential matches* For the title of each Singapore publication in WOS, we implement an algorithm of comparing the similarity of the text of the title and that of a NPL reference. The algorithm generates a 'relative' similarity score for each comparison, and the most relevant potential matches are those that meet a cutoff of the similarity score.
> Step 2: *Refine potential matches* Since Step 1 only identifies the most likely potential matches and the score only has relative meaning, we use another algorithm to create an 'absolute' similarity score for each pair of WOS publication title and NPL reference. Only NPL references that meet a cutoff of the absolute similarity score are kept as short-listed matches.

We manage to retrieve 28,202 pairs of matching NPL and WOS titles by using the Hu–Ly algorithm and 15,526 pairs by the OECD algorithm. There is significant overlap between the two sets so that the combined dataset contains 32,359 unique pairs of NPL references and WOS publications.

We then manually check the validity of the matched pairs of NPL reference and WOS publication. The checking involves verifying not just the title but also other publication information such as author names, affiliations, journal title, volume and issue numbers, and publication date.

Notes

1. Jaffe et al. (1993); Zucker et al. (1998); Thompson and Fox-Kean (2005); Belenzon and Schankerman (2013)
2. See, for example, Audretsch and Feldman (1996); Almeida and Kogut (1999); Hicks et al. (2001); Maurseth and Verspagen (2002); Peri (2005); Belenzon and Schankerman (2009). Jaffe and De Rassenfosse (2016) provided a recent and comprehensive survey of the patent citation and knowledge flow literature.
3. See Yusuf and Nabeshima (2007) for more examples and country experience.
4. Hang et al. (2016) presents a rich account of the history of the research sector of Singapore.
5. Subsumed under the statutory board A*Star (Agency for Science, Technology and Research), these institutes include the Institute of Molecular and Cell Biology, Genome Institute of Singapore, Bioinformatics Institute, Bioprocessing Technology Institute, etc.
6. Some of the big whales that Singapore attracted included Edison Liu, the then Scientific Director of the National Cancer Institute's Division of Clinical Sciences; Sir David Lane; and Jackie Ying, one of the youngest tenured professors at MIT then. Sydney Brenner was the founding chairman of one of the first research institutes, the Institute of Molecular and Cell Biology.
7. Examples of such consortia include the Singapore Cancer Syndicate, the Singapore Stem-Cell Consortium, and the Singapore Immunology Network.
8. By papers authored by Singaporeans, we mean that at least one of the co-authors listed has a Singapore address.
9. We used the WOS classification system only to retain the papers in 'science and technology'.
10. Following JHT, we constructed the control sample by randomly selecting patents that belong to the sample patent technology class and that were filed in the same year.
11. There are thirty-six patent technology fields/sectors, ranging from analysis of biological materials to transport.
12. Sampat and Ziedonis (2004), for example, reported a positive correlation between the incidence of university licensing and patent citations.
13. The Poisson estimator will still generate consistent estimates.
14. Lukach and Lukach (2007) was one of the first to apply PageRank to patents.
15. We also estimated the model using a Probit estimator. The results are similar to those generated by the linear probability estimator and are available upon request.
16. More precisely, these are patents granted to multinationals, which we manually identify with at least one Singapore address.
17. For example, Hu (2004) showed that these MNCs are responsible for most of the patenting originating from Singapore.

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