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From separate systems to a hybrid order: accumulative advantage across public and private science at Research One universities

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Abstract

Drawing on 18 years of panel data for the 89 most research-intensive US universities, this paper examines changing relationships between commercial and academic systems for the dissemination and use of new scientific findings. Increased patenting and commercial engagement on US campuses, I argue, has dramatically altered the rules that govern inter-university competition. From once separate systems with distinct stratification orders, commercial and academic standards for success have become integrated into a hybrid regime where achievement in one realm is dependent upon success in the other. Using observed variable structural equation models, I establish that the integration of public and private science occurred in progressive stages between 1981 and 1998. The implications of that periodization for organizational mobility in a hybrid academic/commercial stratification system are discussed.

Keywords: Accumulative advantage; Institutional change; Intellectual property rights; Status order

1. Introduction

Some 20 years ago, national policy changes formalized US universities' rights to intellectual property (IP) generated with federal research support. In December 1980, Congress passed the Bayh-Dole Act, which allowed non-profit organizations (including universities) and small firms to retain title to IP developed with federal R&D funds.[1] Bayh-Dole was a watershed, because it standardized rules for the ownership and marketing of academic IP, which had previously required individual negotiations between universities and federal funding agencies (Sampat and Nelson, 2000).[2]

A common analytic theme runs through much research on university commercialization in the period since Bayh-Dole.[3] Scholars concerned with the institutional and organizational effects of university research commercialization rely (implicitly or explicitly) on a strong sense that commercial and academic endeavors represent fundamentally different and potentially contradictory arrangements for the creation,

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[1] See Eisenberg (1996) for a detailed examination of the Bayh-Dole Act, and Lee (1994) for a review of early policy changes related to academic patenting and licensing.

[2] Mowery et al. (2001) present convincing evidence that significant university-based patenting and licensing activity preceded Bayh-Dole. The 1980 Act, then, created an impetus and rationale for all universities to enter the commercial arena.

[3] See, for instance, Heller and Eisenberg (1998), Florida (1999), Henderson et al. (1998), Etzkowitz et al. (1998), Powell and Owen-Smith (1998), and Campbell et al. (2000) to name only a few.

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dissemination, and use of new scientific and technical knowledge. This view holds regardless of the policy implications these authors offer. What is novel (or dangerous) about universities' direct engagement in commerce, scholars contend, is the collapse of two distinct institutional systems into a single organizational mission. Importing the rules and standards of commercial science into the university is transformative precisely because this movement alters the institutional logics and organizational arrangements that support academic science.

This paper uses patenting by Research One (R1)[4] universities as an empirical lens to examine the implications of increased commercial activity in the academy. I draw on 18 years (1981–1998) of university-level patent, funding, and scientific impact data to examine the changing relationship between academic and commercial science in the premier US research organizations. Academic (or public) and commercial (or private) science represent distinctive institutional arrangements for the coordination, use, dissemination, and evaluation of scientific findings (Dasgupta and David, 1987, 1994; Packer and Webster, 1996). In the last two decades, universities' widespread adoption of commercial metrics and outcomes has altered the rules that govern competition in the highly stratified world of academic science.

Until recently public and private science remained largely distinct. Publications (the key public science output) were the territory of academia and patents (the coin of the technologist's realm) were concentrated in industry. But as universities became more commercially engaged, the institutional and normative boundaries between the realms blurred. Particularly in the life sciences (Narin et al., 2000), but also in areas such as computational chemistry (Mahdi and Pavitt, 1997), university science has become increasingly important to industrial innovation (Hicks et al., 2001).

At the same time, increased academic patenting indicates shifting boundaries between public and private science within the university by signaling the importation of new mandates and meanings to the academic research mission. Campus scientists patent and publish (Blumenthal et al., 1996). New measures of worth accompany the turn toward academic capitalism (Slaughter and Leslie, 1997). The hybrid scientist–entrepreneur is rapidly becoming the hero of the academic mythos (Zolla-Panzer, 1994), and faculty responses to commercialization manifest the complexities inherent in managing sometimes contradictory commitments (Owen-Smith and Powell, 2001a).

Importing commercial mandates to organizations traditionally dominated by academic practices, then, will alter activities and arrangements on campuses, adding novel criteria to evaluations of actions and altering long-held standards for professional and organizational success. Widespread academic patenting implies that an established set of players (universities) long dominant in the field of public science have started competing in a new arena. For academic research institutions, private sector rationales change established recipes for success and require the creation of policies, procedures, and organizational actors to manage the interface between public and private science uses of the same scientific findings (Kaghan, 2001; McCray and Croissant, 2001; Sampat and Nelson, 2000; Berkovitz et al., 2001) This integration of public and private science orientations on US campuses, I contend, has fractured the status-based stratification order governing achievement in the public science arena and altered the conditions for competition among universities. From separate beginnings, a hybrid institutional system characterized by positive feedback loops across public and private uses of scientific findings has emerged. In its turn, this shift has brought new opportunities for organizational mobility in the status-based accumulative advantage driven reward structure of academic science (Merton, 1968, 1988; Allison et al., 1982; Bentley and Blackburn, 1990).

I begin with descriptive evidence of a pattern of university success at patenting, which is characterized by increasing returns to commercial experience and suggestive of accumulative advantage *across* public and private outcomes. I then turn to observed variable structural equation models of multiple pooled cross-sections to establish the emergence of such relationships and their timing. Finally, I highlight the ways

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[4] Until a recent change in the classification system, Research One was a designation of research intensity applied to universities by the Carnegie Commission on Higher Education. The R1 designation denoted the most research-intensive post-secondary institutions in the United States. In order to qualify as an R1, a university had to receive at least $40 million in federal R&D funding and grant at least 50 doctorates per year.

in which this 'periodized' model of the changing relationship between academic and commercial science provides new insights into empirical patterns of university mobility over the last two decades.

2. Competition, stratification, and accumulative advantage

2.1. In public and private science

The role that positive feedback loops play in establishing and maintaining academic stratification orders has been established at multiple levels of analysis in the social and natural sciences (Cole and Cole, 1973; Allison and Stewart, 1974; Allison et al., 1982; Bonitz et al., 1997; Keith and Babchuk, 1998).[5] In famously biblical terms, Merton (1968, 1988) described accumulative advantage in the words of St. Matthew: "for whosoever has, to him shall be given, and he shall have more abundance".

The Matthew effect reflects a peculiar type of accumulative advantage, where increasing returns to success are driven by peer evaluations based on reputation. Within such a system, chances for mobility are limited, but opportunities and resources can arise in institutional channels divorced from the peer-review system. I contend that the commercialization of university research presents just such an opportunity in the intensely competitive and highly structured game that is academic science.[6]

A different accumulative advantage mechanism may drive commercial achievement on US campuses (Thursby and Kemp, 2002). Universities are not traditionally organized to facilitate successful patenting (Noll, 1998). Academic scientists pursue research in a broad array of fields with little concern for either direct commercial applicability or for existing IP rights. In addition, university innovations tend to be early stage 'proofs of concept', which carry less immediate commercial value (Jensen and Thursby, 2001). Under these conditions, simply identifying and protecting potentially valuable innovations is a difficult task. Organizations that have developed effective procedures to facilitate invention disclosure and patenting may have an advantage as a wide array of organizational and technical capacities must be brought to bear in drafting a viable patent application.

The institutional knowledge built into technology transfer offices, procedures, and standards provides universities with differential capacities to secure patents (Siegel et al., 2002; Berkovitz et al., 2001; Owen-Smith and Powell, 2001b). Universities that develop effective patenting and licensing practices, then, will have an advantage relative to those that do not. Early development of such competencies will convey lasting advantage to the extent that organizational learning stratifies patenting success in a fashion analogous to the Matthew effect. Where public science rewards are stratified by reputation, private science successes, I contend, are structured by cross-campus differences in the development of organizational capacities as universities learn from their private science experiences (Levitt and March, 1988).

2.2. Across public and private science

The Matthew effect holds for academic science and a key private science outcome may also follow a pattern of accumulative advantage. If patenting success is driven by such a mechanism, then importing private science models of information use to the academy amounts to collapsing two similar but distinctively structured institutional systems into a single organizational mission. The interactions of two distinct rule-sets after such a 'collision' can take multiple forms, ranging from the destruction of both systems to their eventual complementary integration.

I contend that public and private science once represented separate accumulative advantage-based

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[5] Note, however, that some econometric studies have raised questions about the direct effect of reputation on the volume of academic outputs (Arora et al., 1998).

[6] Other 'loopholes' exist as well. Consider John Silber's, the chancellor of Boston University (BU), recent defense of his university's practice of bypassing peer-review with direct 'earmarked' subsidies from the US Congress. In a recent interview, Silber defends earmarking as a means to "force your way into" a peer-review system he characterized as an "old boy network". The resources BU garnered without review, Silber contends, have enabled BU to gain ground in competitions for federal grants and contracts: "Our peer-reviewed grants and contracts have increased with every passing year. It is a result of having been able to put together the facilities to bring in the outstanding scientists, who bring in those peer-reviewed grants" (Schlesinger, 2001).

Table 1
University patent and publication impact rankings

University	Percentile rank				Percentage change in rank	
	1981–1983		1996–1998		Patents	Impact
	Patents	Impact	Patents	Impact		
Scientific elite						
Rockefeller University	0.569	1.000	0.639	1.000	7.0	0.0
Washington University	0.569	0.964	0.755	0.916	18.6	−4.8
UC San Diego	0.779	0.940	0.779	0.976	0.0	3.6
Yale University	0.290	0.928	0.686	0.940	39.6	1.2
University of Washington	0.569	0.892	0.848	0.773	27.9	−11.9
Yeshiva University	0.441	0.880	0.232	0.928	−20.9	4.8
University of Chicago	0.290	0.857	0.523	0.845	23.3	−1.2
Patenting elite						
University of Wisconsin	0.988	0.535	0.976	0.500	−1.2	−3.5
Purdue University	0.965	0.309	0.523	0.142	−44.2	−16.7
University of Utah	0.918	0.595	0.802	0.738	−11.6	14.3
Iowa State University	0.918	0.107	0.872	0.178	−4.6	7.1
University of Minnesota	0.906	0.607	0.813	0.547	−9.3	−6.0
University of Rochester	0.883	0.714	0.232	0.690	−65.1	−2.4
UC Davis	0.860	0.369	0.593	0.333	−26.7	−3.6
Founding elite						
MIT	1.000	0.904	0.988	0.904	−1.2	0.0
Caltech	0.976	0.976	0.930	0.964	−4.6	−1.2
UC Berk/UCSF	0.953	0.869	1.000	0.880	4.7	1.1
Stanford University	0.918	0.952	0.965	0.892	4.7	−6.0
Johns Hopkins University	0.848	0.916	0.918	0.952	7.0	3.6
Harvard University	0.872	0.988	0.825	0.988	−4.7	0.0
Mobile						
Pennsylvania State University	0.000	0.261	0.697	0.226	69.7	−3.5
Emory University	0.000	0.488	0.662	0.738	66.2	25.0
Rutgers University	0.000	0.095	0.627	0.488	62.7	39.3
University of Pennsylvania	0.441	0.750	0.941	0.809	50.0	5.9
Columbia University	0.383	0.726	0.837	0.869	45.4	14.3
Arizona State University	0.000	0.130	0.325	0.119	32.5	−1.1
University of Florida	0.651	0.178	0.906	0.154	25.5	−2.4

stratification systems. Over time, however, increasing private science orientations in the academy have enabled the emergence of a hybrid stratification order, where advantage can cumulate within *and* across academic and commercial outcomes. From distinct starting points public and private science have progressively integrated and the systems' interactions have enabled some US universities to leverage success in one arena into achievement in the other.

Consider Table 1, which classifies R1 universities by their relative rankings in terms of scientific reputation and patenting in 2–3-year time periods (1981–1983 and 1996–1998).[7] Rankings are reported in relative (percentile) terms. For instance, Rockefeller University's 1981–1983 patent ranking of 0.569 indicates that this university received more patents in that time period than nearly 57% of R1 organizations.

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[7] The measures that support these rankings are drawn from the Institute for Scientific Information's University Indicators Database and from my coding of the 19,819 US patents assigned to R1 universities. I present more detail on these data in the following sections.

Table 1 sorts R1 universities into four different categories by appeal to their starting and ending points on relative public and private science rankings. Those institutions I have dubbed the ‘scientific elite’ rank above the 85th percentile in terms of reputation[8] in the first time period while falling below that threshold for patenting. In contrast, the ‘patenting elite’ are institutions that rank in the top 15% for obtaining IP without reaching the same level in reputational terms.[9] The ‘founding elite’ ranked above the 85th percentile on both measures and established formal technology transfer offices prior to 1980.[10] Finally, the group of universities I label ‘mobile’ ranked below the 85th percentile on both measures in 1981–1983 but increased their rankings on the patent measure by at least a quartile between the first and last time periods.

The composition of these groups and their patterns of mobility across nearly two decades are instructive. Consider the scientific elite noting first the mix of publicly and privately governed institutions and the presence of both scientific generalist (e.g. Yale) and specialist (e.g. Rockefeller) campuses. These universities are much more successful in reputational than in patenting terms in the period immediately following Bayh-Dole. Nevertheless, the majority of these organizations saw great upward mobility on the private science measure without consequent declines in academic reputation. This pattern suggests that academic reputations can be parlayed into patenting success without damage. Indeed, the relative stability of this group’s reputations across time periods suggests that far from being contradictory, public and private science outcomes became complementary over time.

A similar theme is reflected in the trajectories of the patenting elite. In this group, composed primarily of large state universities, downward mobility in patenting is almost universally matched by declines in reputation. These declines may reflect a shift in academic patenting away from agricultural and mechanical innovations toward biotechnology, semi-conductors and emerging technologies more closely linked to basic science (Henderson et al., 1998). In the aggregate, however, the technological composition of these organization’s patent portfolios does not differ substantially from those of the other three groups. Moreover, close analyses of the patent portfolios of three universities (Mowery et al., 2001) suggest that academic research is not being shifted toward explicitly applied work in the sense that might be reflected in changing publication venues or broad subject areas. Studies that rely primarily on patent measures, however, may miss more subtle shifts in the climate of research on campus. In interviews life scientists report increasing pressure to shift research from animal to human model systems (Owen-Smith, 2000). Human-based research is closer to commercial application. While such shifts are not apparent in publication or patenting measures per se, they may have lasting effects on the academy and point to the limitations of output measures as indicators of broader regime change.

The University of Utah provides an interesting exception to patenting elite’s trend. Its increasing scientific reputation in the context of declining patenting may reflect aggressive entry into the field of genomics. Utah’s location in Salt Lake City, the home of the extensive Mormon genealogical database, may have

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[8] Scientific reputation is operationalized using a standardized measure of publication impact (impact relative to world) reflecting the mean citation impact of a given institution’s journal articles in a given year standardized by the mean citation impact of all articles published in that year. I chose the admittedly arbitrary 85% cutoff for empirical reasons. A higher cutoff (e.g. the 95th percentile) does not provide sufficient variation in campuses to empirically separate ‘single regime’ elites from the small group of universities that dominate the top ranks of both measures. Similarly, lower cutoffs (e.g. the 75th percentile) do increasing violence to the concept of an elite while including so many universities that distinctions between patenting and publishing oriented campuses begin to blur.

[9] Unlike the measure of publication impact, which is standardized to avoid biases introduced by an increasing secular trend in citation rates. I use a simple count of issued patents to operationalize patenting achievement. This unstandardized measure is employed to maintain coherence across inferential and descriptive analyses. Standardizing in a fashion similar to publication impact (e.g. by the total number of patents issued to R1 universities in a given year) does not alter the status ranking described in Table 1.

[10] I follow Mowery and Ziedonis (1999), and Mowery et al. (2001) in making the important distinction between universities active in tech transfer prior to Bayh-Dole and those who entered the patenting game later. The distinction is important for my argument, because early entrants interested in retaining title to innovations developed with federal funding were required to negotiate individual arrangements with funding agencies. Thus, ‘founding’ universities are distinguished by a early and explicit development of patenting and licensing infrastructure as well as by early commercial success. Without exception, those institutions that rank above the 85th percentile on both measures are ‘founders’ in this sense.

contributed to its increasing life science portfolio. Research organizations and firms active in genomics have become increasingly dependent on this storehouse of genealogical information. That interest and the university's location may have helped make Utah a player in a new field important in both public and private science circles. Despite this exception, the pairing of patenting declines with dips in academic prestige further suggests the development of a hybrid stratification system where organizational fortunes in public and private science closely mirror each other.

Both the patenting and the scientific elite's starting points, a high ranking in a single regime, imply that if a hybrid system developed, it did so from largely distinct origins. The small but important founding group, however, represents an instance of early overlap between the two systems and, perhaps, the catalyst for institutional changes leading to integration. While these institutions emphasize the extent to which Bayh-Dole accelerated but did not create university patenting (Mowery et al., 2001), for our purposes they demonstrate the strength of accumulative advantage within and across public and private science. With only one exception, Harvard's dip below the 85th patenting percentile in 1996–1998, these institutions started at the top of both measures and stayed there.

This group's stable success also evidences private science accumulative advantage based on organizational competencies. In part because they negotiated individual IP policies with federal funding agencies prior to Bayh-Dole, these universities have much more extensive experience in patenting and technology transfer than later entrants. The founding elite share more than early infrastructure development, though. Many of their policies and procedures are similar, following the widely emulated 'marketing' approach to technology transfer that de-emphasizes legal and compliance issues in favor of technology marketing and 'service' to faculty (Neuer, 1995). This approach was pioneered at Stanford by Neils Remiers who founded that university's Office of Technology Licensing before going on to direct technology transfer efforts at UC–San Francisco. Reimers also presided over a reorganization of the MIT technology licensing office in the mid 1980s.

The two patenting elite universities that remained in the top 15% are also distinguished by the early development of technology transfer infrastructure. These two schools founded independent technology transfer organizations (the Wisconsin Alumni Research Foundation, WARF, and the Iowa State University Research Foundation) decades before Bayh-Dole. Their persistence among top patentors suggests the importance of experience for continued private science success. Nevertheless, their less stellar public science rankings indicate the possible costs of locating private science competencies outside the core of the university in an era when public and private science seem are becoming more closely integrated (Owen-Smith, 2001). Following this logic, the University of Chicago has recently moved to bring technology transfer capacities that had been housed in the ARCH development corporation in house.

Finally, consider the group of universities I label 'mobile'. This interesting group includes ivy league (Columbia, Pennsylvania) and large state campuses (Florida, Arizona State). In many cases these schools did not patent at all in the 1981–1983 period. All were relative latecomers to technology transfer, creating formal offices in the mid to late 1980s. Nevertheless, these institutions showed dramatic increases in relative patent rankings and, in three cases (Columbia, Emory, and Rutgers) matched private science mobility with sizeable increases in academic reputation. These cases demonstrate the possibility of dramatic mobility in both realms while suggesting that such movement may depend on the ability to achieve in both regimes simultaneously.

3. Modeling the relationship between public and private science over time

I turn to observed variable structural equation models (Joreskog and Sorbom, 1996) of multiple pooled cross-sections of R1 patenting to demonstrate (1) that accumulative advantage holds in private science; and (2) that from separate starting points, two distinct institutional regimes progressively overlapped to create a hybrid 'recipe' for university success. In public science the Matthew effect proceeds through reputation enabled by research capacity. In contrast, accumulative advantage in private science is driven, I contend, by organizational learning in the development of procedures and arrangements for identifying, protecting and managing IP.

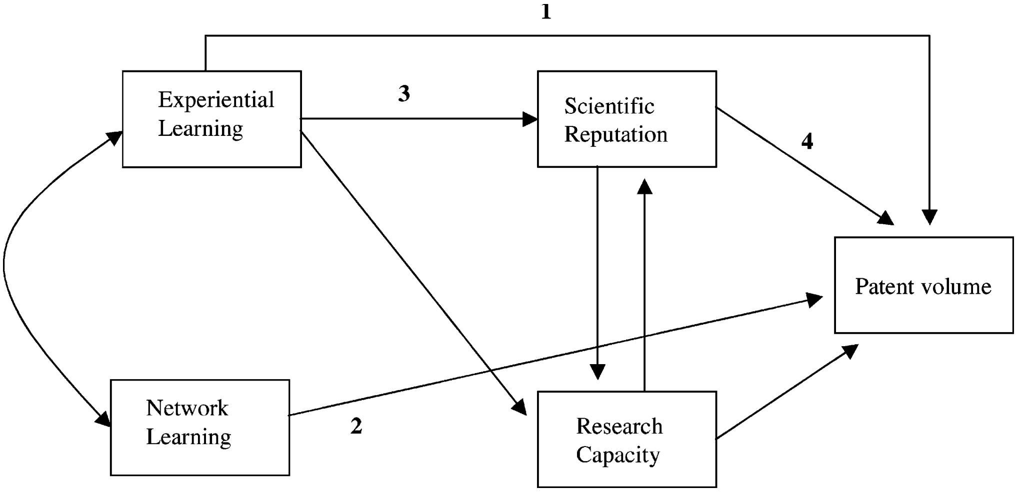

Fig. 1. Conceptual model of Research One university patenting.

Yet neither of these ‘within realm’ mechanisms of accumulative advantage can explain the patterns of stratification and mobility I document above. Instead the development of positive feedback loops across public and private science enabled accumulative advantage mechanisms of stratification to hold within *and* across the realms. On this view, the collision and eventual integration of two distinct regimes for knowledge use reflects a transformation at the core of the university. The particular periodization and process of that integration, I argue, explains the patterns of stratification and mobility highlighted in Table 1.

3.1. Models and measures

Fig. 1 presents a conceptual model relating scientific reputation, research capacity, private science experience, and patent-related network connections to counts of issued patents. The four numbered paths are of primary importance for this argument. Paths one and two test the existence of accumulative advantage in private science. The first arrow, connecting prior patenting experience with current patent volume, will be positive if accumulative advantage holds in private science. Alternately, advantage might cumulate as organizational capacities develop not through experience but through imitation. The second connection, linking network connections with firms to university patenting, will be positive if universities learn to patent, at least in part, by imitating already expert partners.[11]

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[11] Of course ‘experiential learning’ and ‘network learning’ are latent concepts that might be operationalized using numerous indicators. I rely on the two measures described here recognizing that an observed variable framework admits possible biases based on my choice of indicators. Consider two possibilities. First, learning might proceed through forms of network connections other than patent co-ownership. Licensing ties, for instance, are a much more common and less intensive way for universities and firms to connect. Nevertheless, such ties represent an important source of learning that is not captured here as licensing deals offer academic organizations the opportunity to develop legal expertise and boilerplate language relevant to later patent prosecutions. Under these circumstances, we would expect the more restrictive indicator of network learning used here to underestimate the effect of network connections on later patenting. Likewise, using successful patent prosecutions to reflect experiential learning may miss the possibility that organizational learning proceeds from failure or may underestimate the positive effects of prosecuting a smaller number of more complicated applications. More importantly, quantitative analyses at the level of organizational outputs miss informal mechanisms of learning internal to technology transfer offices such as storytelling and analogy building (Owen-Smith, 2002), while under-representing the importance of individual level measures such as faculty incentives to patent (cf. Owen-Smith and Powell, 2001a) on organizational level outcomes. Given these limitations, the analyses I present are best understood to represent broad brush support for the existence and timing of a regime shift while leaving many avenues for further research unexplored.

Of greater interest are the paths numbered three and four. These arrows represent what I have called 'cross-realm' relationships between public and private science. If the integration of commercial and academic science in US universities has resulted in accumulative advantage across the two realms, then I expect path three (representing the effect of patenting experience on scientific reputation) and path four (reflecting the effect of academic prestige upon later patenting) to be positive in the aggregate. More to the point, if public and private science began as distinct systems and became progressively intertwined in the 1980s and 1990s, then I expect these paths to shift from non-significant (or even negative) to positive and significant over time.

3.2. Data and operationalization

I use observed variable structural equation models of panel data for all Research One universities from 1981 to 1998 to test this model.[12] Four types of data operationalize the conceptual model presented in Fig. 1. All US patents assigned to R1 universities from 1976 to 1998 ($N = 19{,}819$) were identified using the United States Patent and Trademark Office's (USPTO) online search engine. Four variables coded from these patents are used in these analyses: (1) *patent volume*, the number of patents assigned to a given university in a given year; (2) *prior patents*, the number of patents assigned to a given university in prior years; (3) *industry assignment*, the number of patents jointly assigned with industrial partners for each university in each year; and (4) *pre-Bayh-Dole patents*, the number of patents assigned to a given university after 1976 but before 1981.

Variables that capture some aspects of university research capacity and scientific reputation were drawn from the Computer Aided Science Policy Analysis and Research database (CASPAR) maintained by the National Science Foundation (National Science Board, 2000). CASPAR integrates information drawn from yearly surveys of post-secondary institutions and federal funding agencies with National Center for Education Statistics and National Research Council data on the same institutions.

Five CASPAR variables provide indicators for this analysis. *Total R&D expenditures* are my primary measure of university research capacity. This measure reflects the total amount of separately budgeted R&D expenditures on each campus excluding spending on clinical trials, training, demonstration, and public service. In essence, then, this variable represents the level of fiscal resources a given campus devotes to R&D. In order to compress the distribution and scale interpretations in terms of percentage rather than unit change I log R&D expenditures in all reported models.

Several exogenous variables were also extracted from CASPAR. They include: (1) industry, R&D expenditures; (2) year end value of endowment assets, federal obligations for R&D; and (3) number of research staff. These variables appear in the model as exogenous explanators of the dependent variable and of endogenous public and private science indicators.

The Institute for Scientific Information's (ISI) University Indicators Database provides my key indicator of scientific reputation. ISI maintains data on publication volume, citation counts, and publication impact for the top 100 US universities. These data span the time period 1981–1998. I use *impact relative to world*—which reflects a university's mean citation impact standardized by the mean impact of all articles published in a given year—as an endogenous indicator of public science reputation at the organizational level. The final variable, *technology transfer age*, captures the time in years since a university first dedicated at least 0.5 full time staff equivalents to patenting and licensing activity. That variable is drawn from the Association of University Technology Managers (AUTM) annual licensing survey.

Table 2 summarizes the variables, providing definitions and data sources and relating specific measures to the concepts I take them to operationalize. The italicized variables are of particular importance as they concretize the conceptual model presented in Fig. 1. Drawing on these variables I propose a non-recursive five equation system to specify my

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[12] While there are 89 research one universities in the United States, this analysis is conducted with 87 organizations as coding and data reporting difficulties forced me to combine two UC campuses (Berkeley and UCSF) and two State University of New York campuses (SUNY Buffalo and SUNY Stony Brook).

Table 2
Factors and indicators with data source and definition

Factors	Indicators	Source	Definition
Scientific reputation	Federal obligations for training	CASPAR	Federal obligations for all fellowship, traineeship and training grant programs in science and engineering; obligations imply funds promised by federal sources not funds actually spent on training (dollars in thousands)
	Citation impact relative to world	ISI	Citation impact of publications in all fields from a single institution relative to the impact of all academic publications in a given year; a standard measure of the overall impact of a university's publications
Research capacity	*Total R&D expenditures*	CASPAR	Total amount of separately budgeted research and development expenditures in science and engineering from all sources; expenditures imply actual amounts spent in a given year excluding training, public service, demonstration, and clinical trials (dollars in thousands)
	Industry R&D expenditures	CASPAR	Total amount of separately budgeted research development expenditures in science and engineering from industrial sources (dollars in thousands)
	Research staff	CASPAR	Sum of S&E faculty, post-docs, graduate students, and research staff
Experiential learning	Technology transfer age	AUTM	Time in years since the university first dedicated at least 0.5 FTEs exclusively to patenting and licensing activities
	Prior patents	Coded	Number of patents assigned to a university in prior years
	Pre-Bayh-Dole patents	Coded	Number of patents assigned to a university between 1976 and the passage of the Bayh-Dole Act in December 1980
Network learning	*Industry assigned patents*	Coded	Number of university patents jointly assigned with a for profit firm/corporation
Institutional wealth	Endowment assets	CASPAR	Book value of endowment assets
Patent volume (dependent variable)	*Patent volume*	Coded	Number of US patents assigned to a university in a given year

All variables available yearly for 87 Research One universities from 1981 to 1998. Italic text indicates an endogenous variable. Regular text indicates an exogenous variable.

conceptual model.

$$\begin{aligned}\text{Patents}_t = {} & \beta_1(\text{impact}_{t-1}) \\ & + \beta_2 \log(\text{R\&D Expenditures}_{t-1}) \\ & + \beta_3(\text{prior patents}_{t-3}) \\ & + \beta_4(\text{industry assignment}_{t-3}) \\ & + \varphi_1(\text{TTO age}_{t-1}) \\ & + \varphi_2 \log(\text{endowment}_{t-1}) + \zeta_1 \end{aligned} \tag{1}$$

$$\begin{aligned}\text{Impact}_{t-1} = {} & \beta_5 \log(\text{R\&D Expenditures}_{t-1}) \\ & + \beta_7(\text{prior patents}_{t-3}) \\ & + \varphi_3 \log(\text{R\&D observation}_{t-1}) + \zeta_2 \end{aligned} \tag{2}$$

$$\begin{aligned}& \log(\text{R\&D Expenditures}_{t-1}) \\ & \quad = \beta_6(\text{impact}_{t-1}) + \beta_8(\text{prior patents}_{t-3}) \\ & \qquad + \varphi_4 \log(\text{staff}_{t-1}) + \zeta_3 \end{aligned} \tag{3}$$

$$\text{Prior patents}_{t-3} = \varphi_5(\text{PBD patents}) + \zeta_4 \tag{4}$$

$$\text{Industry assignment}_{t-3} = \varphi_6 \log(\text{industry expenditure}_{t-3}) + \zeta_5 \quad (5)$$

This model is identified on both the rank and order conditions (Maddala, 1994) and includes a temporal lag structure that corrects for some aspects of serial auto-correlation in pooled cross-sections while taking observed delays into account.[13] Eqs. (1) and (2), the patent and impact equations, respectively, are most central to the arguments I present here.

The patent equation tests hypotheses about private science accumulative advantage and about the cross-realm effects of public science prestige on levels of private science outcomes. Where patenting and publishing are mutually reinforcing activities, a better organizational reputation for high quality science will increase patenting on campus. Thus, H_1: $\beta_1 > 0$.

Likewise, the direct relationship between prior patents[14] and current patents will be positive if accumulative advantage drives accomplishment in private science. Thus, H_2: $\beta_3 > 0$. Finally, in the absence of direct patenting experience, universities might develop private science capacities via relationships with experienced partners. Where universities have the capacity to learn from firms, patenting jointly with industrial partners will positively affect later patents. Thus, H_3: $\beta_4 > 0$.

The impact equation provides another insight into the relationship between public and private. Where the patent equation tests the relationship between prior patenting and publication impact, this equation examines the reciprocal relationship between academic prestige and later patenting. As with Eq. (1), if the relationship between public and private science is characterized by mutually reinforcing feedback loops rather than contradictory dynamics, then publication impact will have a positive direct effect on later patenting. Thus, H_4: $\beta_7 > 0$.

Eq. (2) also provides a further test of the Matthew effect in public science. The reputation-based logic of accumulative advantage in this realm relates scientists' prestige and resources (e.g. grant funds) to earlier reputation. In essence the single blind peer-review process that dominates grants and publication in the natural science explicitly links resources and reputation (Chubin and Hackett, 1990). For this reason, the impact equation includes a variable capturing the level of federal obligations for R&D. Unlike expenditures measures, which represent the actual amount an organization spends on research and development, obligations represent the total amount allocated to R&D on a campus by federal granting agencies. This measure offers an indicator of academic reputation that focuses more directly on resources made available through reputational channels. Thus, if the Matthew effect holds in public science, I expect H_5: $\varphi_3 > 0$.

Clearly other paths in this model might test interesting hypotheses.[15] Nevertheless, these propositions represent the core of my argument about the changing relationship between public and private science. Estimating this model across multiple time points and comparing the pattern of effects will illuminate significant longitudinal shifts in the relationship between academic and commercial uses of science while explicitly testing hypotheses 1–5.

3.3. Estimation procedures

I turn to a 'stacked time period' model specification to enable consideration of qualitative changes in the relationships among indicators over an 18-year time period. Rather than estimate the model for the

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[13] I chose the t, $t-1$, $t-3$ lag structure for analytic reasons. In this sample of patents, the mean time from filing to issue is more than 30 months. If prior patenting experience has an effect on later patent volume, then the relevant measure of experience is the number of patents assigned to a university at the time when current patents were filed. Because these data are annual, I opt for a 3-year lag between current and prior patents. Thus I argue that the relevant measure of private science experience for explaining patent volume in, for instance, 1990 is the number of patents a university was issued three years earlier, in 1987. Sensitivity analyses were conducted with a number of alternates to the t, $t-1$, $t-3$ lag structure, but this specification was best-fitting.

[14] I created this lagged endogenous variable using a Kocyk distributed lag structure beginning at 3 years. Kocyk lags assume that the effects of a lagged variable decline smoothly and monotonically with time . Thus, the effect of prior patenting here is distributed across of a number of time periods allowing a more realistic model specification than an aggregated count of prior patents while mitigating the biasing effects of serial auto-correlation in panel data (Studemund, 1993).

[15] For instance, the relationship between prior patents and R&D expenditures (β_8 in Eq. (3)) provides insight into patenting's effects on research capacity and thus into resource scarcity arguments for the growth of university commercialization. If patents provide an alternate route to resources for R&D, then this coefficient will be positive.

full 18-year pooled cross-section, a strategy that forces all relationships to remain constant over time, I simultaneously estimate the model for six 3-year time periods to explicitly test the effects of imposing equality constraints on key coefficients across time.[16] This strategy allows development of a best-fitting model specification that takes into account longitudinal changes in public/private science relationships, thus speaking directly to changing recipes for R&D success on R1 campuses.

I simultaneously estimated the model for all six time periods using full information maximum likelihood (FIML) methods.[17] The model was first estimated without any equality constraints across time periods (the full model). The key relationships between public and private science indicators were then progressively constrained to equality, in effect creating a nested set of 'reduced' models. χ^2 difference tests were used to determine whether additional equality constraints hindered model fit relative to the full model.[18] The null hypothesis is that the model-implied covariance matrix, Σ, was identical to the observed covariance matrix, $\boldsymbol{S}$, at the $P > 0.10$ significance level.[19] This approach allows discussion of findings from a single best-fitting model that incorporates multiple equality constraints. In all cases, models were estimated with error covariances among exogenous variables freed, and those among endogenous variables diagonalized with the exception of the model-implied relationship between industry assignment and prior patents.

4. Findings

Table 3 presents the coefficient values for each of the endogenous relationships in the model (coefficient values for exogenous variables are presented in Table 4). The dependent variables for key linear equations in the model are the rows, independent variables the columns. To get a sense of changes in the relationship between two variables across the six time periods, pick a column and read down. Notice first the patterns of equality (evidenced by coefficient values that remain fixed across time periods) built into the best-fitting model.

The first column of Table 3 presents findings relevant to hypothesis 1, that publication impact will have a positive effect on patenting, indicating growing integration between public and private science. This hypothesis receives support only in the last two time periods.[20] The coefficient's shift from non-significant to positive and significant in the 1993–1995 time period is accompanied by a nearly five-fold increase in magnitude. The implication here is straightforward, in the mid 1990s academic reputation and patent volume became positively related with universities receiving (ceteris paribus) a net return of approximately 2.7 patents for each unit increase in reputation as measured by publication impact. By this time period, having highly cited papers led directly to increased patenting on US university campuses.

Hypothesis 2 relates prior patents to current patents to test the existence of simple accumulative advantage in private science. This hypothesis receives strong support in all periods except 1981–1983. In that period,

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[16] These six time periods (1981–1983, 1984–1986, 1987–1989, 1990–1992, 1993–1995, and 1995–1998) balance the need to maximize the number of periods while maintaining a reasonable sample size within each pool.

[17] Full information maximum likelihood implies that there are enough degrees of freedom available in the observed variance covariance matrices to enable estimation of all unknown regression parameters. Maximum likelihood estimators are particularly robust for pooled cross-section analyses where the distributional characteristics of variables are unsuited to least squares estimation techniques (Sayrs, 1989).

[18] See Appendix A for more detail on the process by which equality constraints were established across time periods.

[19] Unlike most significance tests using full and reduced model specifications, χ^2 difference tests here place the investigator on the wrong side of the null hypothesis. Where such tests usually hope to reject the null, here we hope to accept the null hypothesis that observed and estimated matrices are indistinguishable. Under this rubric, a statistically significant χ^2 implies that the extra equality constraints imposed upon the reduced model hindered the fit of the model relative to the (less constrained) full specification. Because we are hoping to accept the null, the accepted critical value ($P < 0.05$) amounts to accepting a well fitting constrained model if the observed relationships could have happened by chance in one of every 20 samples. Since accepting the null here is tantamount to accepting one's theory, I follow Hayduk (1987, p. 161) in rejecting the null at the 0.10 significance level.

[20] Notice that the coefficients remain the same for the first four and last two time periods. This is the result of the equality constraints imposed on the best-fitting model. Imposing such constraints forces the magnitude of a coefficient as well as its direction to remain constant.

Table 3
Endogenous coefficients by dependent variable and time period 1981–1998

Dependent variables	Years	Independent variables				
		Publication impact	R&D expenditure	Prior patents	Industry assignment	R^2
Patents (SE)	1981–1983	0.58 (0.43)	2.65^{**} (0.44)	−0.02 (0.02)	0.48^{+} (0.26)	0.17
	1984–1986	0.58 (0.43)	2.65^{**} (0.44)	0.67^{**} (0.07)	−0.64 (1.55)	0.62
	1987–1989	0.58 (0.43)	2.65^{**} (0.44)	1.20^{**} (0.09)	−2.41 (2.02)	0.54
	1990–1992	0.58 (0.43)	2.65^{**} (0.44)	0.94^{**} (0.06)	0.53 (0.78)	0.53
	1993–1995	2.69^{**} (0.96)	7.06^{**} (0.99)	0.86^{**} (0.05)	−0.06 (0.63)	0.50
	1996–1998	2.69^{**} (0.96)	7.06^{**} (0.99)	1.39^{**} (0.07)	−0.39 (0.67)	0.35
Publication impact	1981–1983		-1.71^{**} (0.10)	0.003 (0.002)		0.50
	1984–1986		-1.71^{**} (0.10)	0.018^{+} (0.007)		0.55
	1987–1989		-1.71^{**} (0.10)	0.023^{*} (0.007)		0.50
	1990–1992		-1.71^{**} (0.10)	0.012^{**} (0.002)		0.51
	1993–1995		-1.93^{**} (0.14)	0.012^{**} (0.002)		0.53
	1996–1998		-1.93^{**} (0.14)	0.012^{**} (0.002)		0.52
R&D expenditure	1981–1983			0.002 (0.001)		0.77
	1984–1986			0.000 (0.006)		0.80
	1987–1989			-0.004^{*} (0.002)		0.77
	1990–1992			-0.004^{*} (0.002)		0.78
	1993–1995			-0.004^{*} (0.002)		0.80
	1996–1998			-0.004^{*} (0.002)		0.77
Model fit		$\chi^2(170) = 998.44$	Critical $N = 194.45$	$N = 1043$		

R^2 represents the squared multiple correlation for the complete linear equation modeling each dependent variable.

$^{+}$ $P \leq 0.10$, two-tailed tests.

* $P \leq 0.05$, two-tailed tests.

** $P \leq 0.01$, two-tailed tests.

hypothesis 3, relating joint IP ownership with firms, is marginally supported. Accumulative advantage in patenting, it seems, proceeds through the development of organizational procedures and competencies in technology transfer. Immediately following the passage of Bayh-Dole, those capacities were primarily developed through collaborations with industry, while in later years, direct experience with patenting yields increased returns. Hypothesis 4 tests the effect of patenting upon scientific reputation, finding support after 1984, when prior patents positively and significantly affect later citation rates. Soon after Bayh-Dole, then, universities that patented extensively saw returns to that private science activity both in terms of increases in later patenting and in terms of returns to academic reputation. Finally, the consistently positive effect of federal R&D obligations on later publication impact (Table 4) suggests that Matthew effect drives public science reputation across the entire time period.

The consistent pattern of support for all five hypotheses substantiates the role accumulative advantage plays in stratifying a key private science outcome while supporting the proposition that increased research commercialization has led to a fundamental change in the rules by which scientific success is attained on US campuses. From separate beginnings, the distinctive realms of public and private science came to be integrated for R1 universities. This overlap occurred in discrete stages, implying shifting opportunities for mobility in different time periods. I turn to a closer examination of qualitative changes in model coefficients and mobility patterns across multiple ‘types’ of universities to examine some of the effects of a shift toward a hybrid institutional regime for university science.[21]

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[21] In essence, this model is intended to capture increasing complementarities between commercial and academic uses of scientific findings developed on university campuses. A more common method of testing for such complementarities involves a form of ‘claiming the residual’ (Arora, 1996; Arora and Gambardella, 1990; Athey and Stern, 1998). In essence, this approach estimates fully reduced (single equation) least squares models of the

5. Emerging orders and organizational mobility

A quick perusal of Table 3 suggests that there are four key shifts in the statistical model between 1981 and 1998. The first time period (1981–1983) is different from the next two (1984–1989).[22] Likewise, the 1990–1992 time frame differs from those preceding and following (1993–1998) it. As these qualitative changes are difficult to read in Table 3, I turn to a graphic representation to capture periodization in the changing relationship between public and private science over time. Fig. 2 summarizes these significant shifts by diagramming the endogenous portion of the model complete with significant paths and an indication of the direction of key relationships.

The first frame of Fig. 2 (period I) encapsulates relationships in the time period where the model is weakest for explaining patenting (notice the relatively low R^2 for the first row of Table 3). Clearly research capacity matters here and accumulative advantage in private science proceeds (though weakly) through shared patenting with firms. Soon after the passage of Bayh-Dole, many universities had not developed organizational units responsible for technology transfer. Patenting did not have a particularly high profile on most university campuses,[23] and, as the non-significant relationship between the patenting and impact variables suggest, the realms of public and private science remained largely separate. Between 1981 and 1983 patenting success was driven largely by a university's capacity to fund research and, perhaps, by its interactions with industry.

The first important shift in this system is apparent in period II, which saw a change within private science. Where patent specific network connections appear to be the route to early patenting success, first hand experience absent a partner became an important factor in later development of IP. This transition may have resulted from the first rush to develop internal organizational capacities for technology transfer, from an influx of new entrants to the patenting game[24] from early publication of success stories at founding institutions such as Stanford and MIT, and from the increasing legitimacy of academic forays into private science evidenced by expanding legislation governing university technology transfer (Lee, 1994).

This time period also witnesses the first evidence of cross-realm accumulative advantage with a significant positive effect of patenting on later publication impact. This relationship suggests that patenting increases the visibility of a school's published research. As this period also saw the development of lucrative royalty streams on some of the most visible patenting campuses (for instance from the Cohen-Boyer patent, Stanford and UCSFs joint patent on basic gene splicing techniques), the positive relationship might

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endogenous (patent and impact) measures and correlates the residuals of those regressions. If the two measures are indeed complementary, then those residuals should be positively correlated. If, as I have argued, public and private science have become increasingly complementary over the last two decades, then the correlations among residuals from the reduced equation should be stronger in the 1990s than in the 1980s. In unreported robustness analyses I performed these tests finding that by this logic public and private science have always been highly complementary activities on university campuses (residuals from the fully reduced equations are correlated at 0.69 for the time period from 1981 to 1989). However, the same analyses suggest that this complemetarity has increased throughout the 1990s (residuals are correlated at 0.70 for the period 1990–1992 and at 0.74 for 1993–1998). Despite the similarity between these findings and the shifting relationships documented in the following section, I opt to present more complicated models that capture changes in the significance of direct reciprocal effects between endogenous variables. My primary interest is to document the shifting relationship between indicators of public and private science engagement. Thus, this approach includes empirically generated (see Appendix A) equality constraints that build such shifts into the estimated model rather than simply separating independent regressions by time period. More importantly, this approach enables analyses of the ways in which the particular periodization of these shifts provide insights into organizational mobility under conditions of institutional change.

[22] Consider Table 3 and notice the declining significance of industry assignment's effect on patenting, and the newly significant effect of prior patents on current patents in the 1984–1986 time period. These transitions in the statistical model represent 'structural shifts', qualitative changes in the pattern of coefficients in a system. For the purposes of this article, a structural shift occurs when a coefficient gains significance, loses significance, or flips sign.

[23] Nearly 1/4 (20) of the universities in this sample were issued no patents during this three year time period. In contrast, only four campuses went patentless in the following period (1984–1987).

[24] Note that this time period also saw declines in the average impact of academic patents as measured by prior art citations (Henderson et al., 1998). Rather than indicating a shifting priorities in university R&D, however, this decline and a subsequent increase appears to be a function of these 'entrants' learning to identify and develop potentially valuable IP (Mowery and Ziedonis, 2002; Mowery et al., 2001).

Table 4
Exogenous coefficients by dependent variable and time period 1981–1998

Dependent variables	Year	Independent variables					
		TTO age	Endowment assets	R&D observation	Staff	PBD patents	Industry expenditure
Patents (SE)	1981–1983	0.13 (0.05)**	0.40 (0.29)				
	1984–1986	0.06 (0.05)	−0.04 (0.21)				
	1987–1989	0.08 (0.06)	0.02 (0.28)				
	1990–1992	0.23 (0.06)**	−0.20 (0.29)				
	1993–1995	−0.05 (0.06)	−0.50 (0.30)				
	1996–1998	−0.21 (0.09)*	−1.19 (0.51)*				
Publication impact	1981–1983			1.70 (0.10)**			
	1984–1986			1.61 (0.09)**			
	1987–1989			1.52 (0.09)**			
	1990–1992			1.53 (0.09)**			
	1993–1995			1.66 (0.12)**			
	1996–1998			1.52 (0.12)**			
R&D expenditure	1981–1983				0.93 (0.08)**		
	1984–1986				0.82 (0.08)**		
	1987–1989				0.89 (0.09)**		
	1990–1992				0.96 (0.08)**		
	1993–1995				1.03 (0.06)**		
	1996–1998				1.08 (0.08)**		
Prior patents	1981–1983					−0.06 (0.06)	
	1984–1986					0.21 (0.01)**	
	1987–1989					0.19 (0.01)**	
	1990–1992					0.28 (0.02)**	
	1993–1995					0.37 (0.02)**	
	1996–1998					0.36 (0.03)**	
Industry assignments	1981–1983						0.48 (0.18)**
	1984–1986						0.02 (0.02)
	1987–1989						0.04 (0.02)
	1990–1992						0.06 (0.07)
	1993–1995						0.06 (0.08)
	1996–1998						0.34 (0.14)*
Model fit		$\chi^2(170) = 998.44$	Critical $N = 194.45$	$N = 1043$			

* $P \leq 0.05$, two-tailed tests.
** $P \leq 0.01$, two-tailed tests.

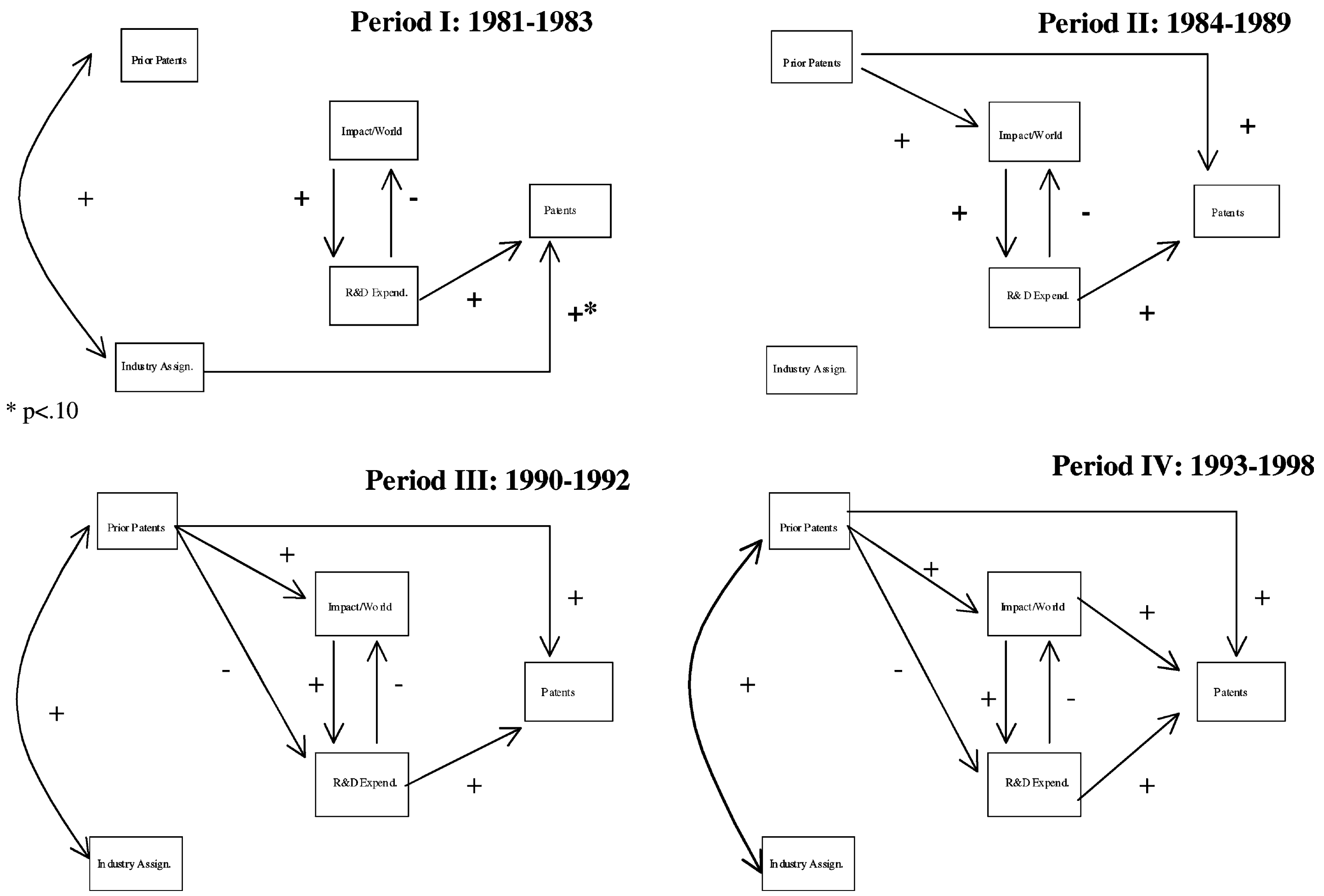

Fig. 2. Significant changes in the endogenous model over time, 1981–1998 (all included paths are significant at $P < 0.05$).

also reflect increasing returns to research capacity resulting from successful marketing of university IP. The lack of any significant direct relationship from patenting to R&D expenditures in this time period and the persistent negative relationship between R&D spending and publication impact mitigates against this interpretation.[25]

Turn your attention to the frame labeled 'period III'. The only significant change here is the addition of a negative direct path between prior patenting and R&D expenditures. This negative effect, however, is a result of controlling for the positive indirect effect of patenting on expenditures through publication impact.[26] This suggests further integration of public and private science reward systems as research capacity returns to patenting accrue only through the indirect mechanism of academic reputation. As the negative direct relationship between prior patenting and research expenditures suggests, universities that attempt to appropriate resources from IP may be in for a shock if they do not also attend to their academic profile. Under these conditions patents are valuable to universities in large part because they increase institutional reputations by advertising success, broaden audiences for research and, perhaps, attract potential collaborators. Extensive patenting enables universities to leverage higher public science status from private science accomplishments; in turn, increased prestige pays dividends in research capacity.

Establishing IP rights to academic findings does not yield direct research capacity benefits. Indeed, Sine et al. (2001) find evidence of a 'halo effect' in university patent licensing whereby institutional prestige leads to increased licensing revenues which, in turn, lead to greater patenting productivity. This pattern is very similar to the patenting → reputation → capacity → patenting cycle documented here and may reflect the increasing importance of private science revenue as a source of unrestricted income that can be used for strategic advancement of a university's public and private science agendas.

As Michael Crow, the executive vice provost at Columbia noted in a recent interview about that university's royalty income: "This is an income stream that is absolutely critical to us. It is the single, most important source of free and clear funding. Everything else comes with a string attached" (Babcock, 2000). Evincing similar beliefs, Stanford University has turned its significant equity returns to the creation of a university-wide fellowship fund to attract and retain talented graduate students. Likewise, Carnegie Mellon University has invested more than $25 million from its equity stake in the web search company Lycos in its computer science department, funding multiple endowed chairs and constructing new research facilities (Florida, 1999).

In period III there is increasing evidence of a hybrid stratification order where capacity returns to both public and private science depend upon a university's academic reputation. Under these conditions, universities that rush to patent in hopes of overcoming the negative effects of lower public science status may face significant unintended consequences if they do not simultaneously look to the maintenance and development of their academic reputations. For the first time, in period III, there is a new system for the use and dissemination of academic findings that merges aspects of public and private science.

The integration of public and private science in this model is complete by the 1993–1995 period. Consider the final frame of Fig. 2, which I label 'period IV.' In this time period, the addition of a direct and positive link between publication impact and patent volume completes the cross-realm connections, establishing a positive feedback loop across public and private

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[25] This negative relationship is robust in the fully reduced form of the impact equation (run as a simple multivariate regression). It is stable if the assumption of simultaneous reciprocal causality between expenditures and impact is broken in FIML estimates, if only federally funded R&D expenditures rather than total expenditures are used to represent research capacity, and if the model is run without any prior patenting variables. Likewise, a more direct relationship between research expenditures in science and engineering fields alone and publication impact in those fields alone remains negative. Considering scatter plots of the two key variables (impact/world and log(R&D expenditure)) suggests that a university outlier may be the cause of the negative relationship. Rockefeller University, a small relatively specialized research one institution focusing on research, graduate and post-graduate training in the biomedical sciences, spends relatively little on R&D in comparison to its less specialized peers but has the highest publication impact rating in every year I model. Removing Rockefeller from the dataset and re-estimating, however, only increases the magnitude of the negative relationship.

[26] Models that exclude this indirect effect find a positive and significant effect of expenditures on patenting, but fit less well than those reported.

science that, in my view, represents a key shift in the rules that govern university R&D. In the period 1993–1998, the transition from separate public and private science systems governed by different rules and largely independent stratification orders to a hybrid system, where success in one realm requires achievement in the other is complete. For this group of research-intensive universities, importing commercial logics to a research mission that was once dominated by public science rules for knowledge dissemination had a dramatic effect on recipes for successful competition in a relatively short, 18 year, time period. But if the rules of the game changed dramatically as a result of increasing commercialization, what effect did those changes have upon the separate and seemingly stable accumulative advantage-based stratification orders characteristic of public and private science?

5.1. Periodized change and opportunities for mobility

Increased research commercialization has transformed the rules that govern university competitions for reputation and resources. Those alterations, I argue, shook up the stable stratification orders that governed success in public and private science and provided opportunities for dramatic mobility as the once separate systems became integrated.[27] But those opportunities did not arise in a vacuum. Both public and private science were highly stratified at the outset, and the hybrid system that enables advantage to cumulate across the realms emerged progressively. Hence, mobility will be conditioned by a university's starting point and the timing of its entry into the private science game.

Recall that Table 1 separated R1 universities into four categories based on public and private science rankings in the 3 years immediately following Bayh-Dole. These categories represent distinctive starting points and offer the opportunity to examine the differential effects of institutional changes wrought by increased academic patenting. Fig. 3 presents public and private science trajectories for the scientific elite, patenting elite, founding elite, and mobile universities. Each frame in the figure represents one group of universities, presenting 3-year moving average trends in mean publication impact (the dashed line) and aggregate patent volume (the solid line). Each panel is further separated into the four time periods that saw significant shifts in the relationship between public and private science (from Fig. 2).

Fig. 3 documents the relationship between starting points, mobility, and periodized transformations in an institutional regime. Recall the overall patterns highlighted in Table 1. In the aggregate, founding universities remained elite on both public and private rankings, the scientific elite matched sometimes dramatic increases in patent rank with stable public science rankings, the patenting elite saw aggregate declines in both patent rank and ranking based on publication impact, and a diverse group of schools, the mobile universities, saw dramatic increases on one or both measures from non-elite starting points.

Changes in rankings occurred in the context of aggregate increases in both patenting and publication impact for all four groups. Indeed, all four frames in Fig. 3 witness increases in both trends across the entire time period with very similar patterns of increase in the 1990s. The differences in mobility captured in Table 1 reflect changes in the relative position of these organizations on public and private science measures. While the rising tide carried all boats, it carried some further than others. Increases on both public and private science measures were matched by dramatic shifts in the relative rankings of universities. Such changes can be understood in the context of the progressive shift from separate systems to a hybrid order.

Consider period II which saw the first direct connection between public and private science. Fig. 3 suggests that the model of progressive integration across realms does a better job of explaining the relative upward and downward mobility of the mobile institutions and the patenting elite than it does at explaining the persistent success of the founding and scientific elite. In the case of the patenting elite, period II saw stable amounts of patenting matched by a decline in publication impact, a pattern that is entirely consistent with the positive relationship between patenting and impact highlighted in Fig. 2. Likewise, the most mobile universities matched increased patenting with growth in publication impact over this period.

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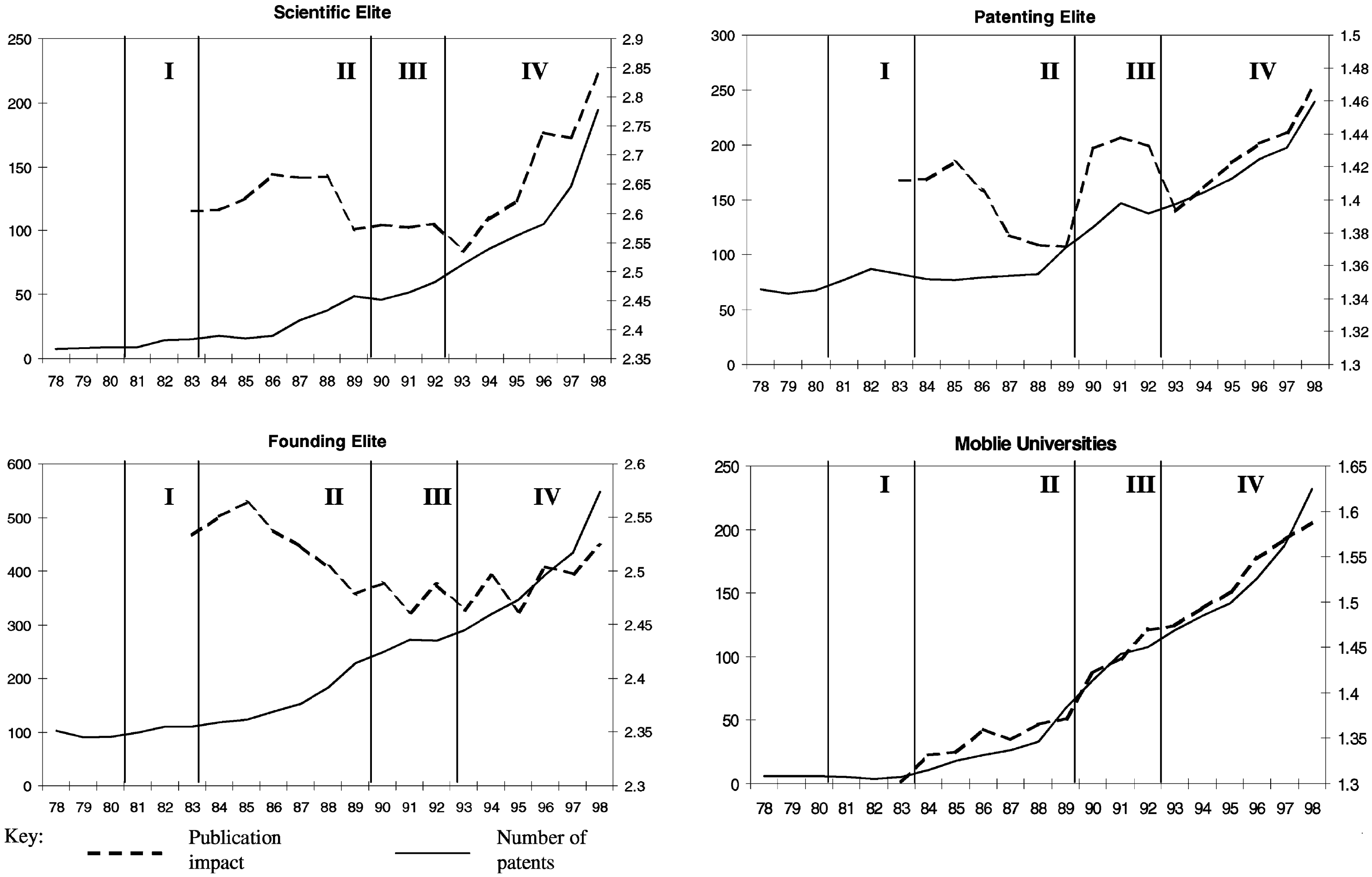
[27] This increasingly complex system may signal unforeseen dangers to universities as feedback loops and indirect effects may increase the potential for negative unintended consequences to commercialization (cf. Behrens and Gray, 2001).



Scientific Elite

Patenting Elite

Founding Elite

Moblie Universities

Fig. 3. Public and private science trends by university position and time period, 3-year moving averages.

The pattern for the scientific and founding elite is less clear. The founding elite matched a decline in public science reputation with an aggregate increase in patenting and the scientific elite saw a more volatile relationship between increased patenting and publication impact. These patterns have two implications. First, the period II link between patenting and scientific reputation may not have been driven by the cross-realm connections on the most successful public science campuses; and second, public science returns to patenting may come more easily at lower prestige levels. In this time period both the patenting elite and the mobile universities had significantly lower publication impact scores than the founding and scientific elite. The less than clear relationship between patenting and reputation for the latter two groups may simply be a function of decreasing possibilities for upward mobility at the top of an established stratification system.

Period III follows a similar pattern with patenting elite and the mobile campuses closely matching patterns of public and private science change while the founding and scientific elite saw less clear relationships. For the patenting elite and mobile universities, period III brought increases in both patenting *and* reputation. Period IV—encompassing the completion of a positive feedback look across the realms of public and private science—witnessed close linkages between upward trends on both measures for all four groups of universities. In this time period, the new, hybrid system enabled cross-realm accumulative advantage and allowed trends in both realms to stabilize.

Patterns of patenting activity in the periods of transition between separate systems and a hybrid order (1984–1993) explain relative changes in rankings. The mobile campuses moved dramatically relative to other universities because they began to increase patenting in a period where private science outcomes carried returns to public science reputation. Likewise, the patenting elite's declining public science rankings can be associated with stable levels of patenting through this time period. Less clear relationships between the realms hold for the scientific and founding elites in this period, perhaps reflecting the negative effects institutional upheavals on established elites. The negative effects on these groups were not strong enough, however, to prevent them from maintaining their positions of relative dominance under the new rules of the game. By the time those rules (a hybrid public/private science system for the dissemination and use of knowledge) were in place, the mobile and patenting elite universities had established trajectories that explain their relative patterns of mobility on public and private science rankings.

6. Conclusions and implications

One lasting effect of increased research commercialization at universities has been a profound change in the relationship between public and private science systems for the dissemination and use of new scientific knowledge. Soon after Bayh-Dole, public and private science represented largely separate and potentially contradictory institutional regimes with distinct stratification orders. Over nearly two decades, increased university commercialization and patenting occurred in the context of a shift from separate stratification systems to a hybrid order where advantage cumulates across the two different realms. Under such conditions success in one institutional arena is largely dependent upon a university's activities in the other.

Important changes are afoot on US university campuses. The analyses presented here suggest that beyond first-order difficulties, such as conflicts of interest associated with increased commercialization, there has been a systematic shift in the recipes and standards for success that govern inter-university competition. The particular timing of these transitions accounts for patterns of organizational mobility that are otherwise difficult to explain.

This fundamental change in the rules governing universities' knowledge dissemination practices opened a window for dramatic mobility that may not have been possible in either system alone. The period between 1984 and 1993 saw important changes in the relationship between public and private science and these changes enabled one diverse group of universities (the mobile campuses) to leverage academic returns from commercial outputs. This pattern of increase in both realms established a trajectory that stood these schools in good stead once the relationship between public and private science settled down into a positive feedback loop. Another group of universities, the patenting elite, lost position relative to their competitors as a result of their failure to establish a joint trajectory in the period of transition from separate systems to a hybrid order.

It is important to note, though, that the methods and data I draw upon in this paper are sufficient only to document these shifts and their effects in broad brush-strokes. Further research is needed to understand the mechanisms by which universities learn to patent more effectively. Work that draws upon multiple indicators of commercial achievement, disaggregates public and private science measures by research area, and that focuses more explicitly on individual incentives to patent, relationships among units within universities, and variations in organizational arrangements for technology transfer will help nail down the timing and effects of the shifting relationship between public and private science. Likewise, detailed qualitative research examining the attitudes and practices of individual faculty, research groups, and licensing offices is necessary to fully grasp the subtle changes brought about by the emergence of a hybrid regime for the discovery and use of new findings on US campuses.

Understanding the effects of research commercialization on US university campuses requires that attention be paid to the second-order and unintended consequences of private science involvement. Far from representing simple problems amenable to ad hoc solutions, the changes at work in the US public research system are comprehensive and center upon shifts in the institutional regimes that govern the knowledge use, inter-organizational competition, and reward systems in the academy.

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Appendix A. Establishing equality constraints in the stacked time period model

Where models run on a single pooled cross-section force coefficients to remain constant over time, simultaneously estimating models on multiple pools provides insights into the timing and sequence of change. I begin with a discussion of my model fitting strategy, highlighting the process that led to a single model inclusive of multiple equality constraints across pools.

Models were estimated for six 3-year time periods.[28] These 3-year pools form the basis of my findings about over time change in the relationship between public and private science. In order to establish the periodization of that change, I test hypotheses about the equality of sets of relationships across sets of time periods.[29] Table A.1 details the steps I took in creating a model that captures equality constraints across a variety of time periods and sets of model coefficients.

I first estimated a full model (model 1) which imposed no equality constraints on any set of coefficients in any time periods. Essentially this model presupposes the opposite of a pooled model by assuming that all endogenous relationships in my model are different in each 3-year time period. This full model is basis for tests of the effects of increasing equality constraints across time periods. Model 2 forces all endogenous relationships to equality across all the time periods (essentially mirroring the pooled

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[28] Period 1, 1981–1983; period 2, 1984–1986; period 3, 1987–1989; period 4, 1990–1992; period 5, 1993–1995; and period 6, 1996–1998.

[29] I will not present model fit statistics for every equality hypothesis that I tested here. Instead, I focus on documenting the 'trail' I followed in the development of the model I report. I also make no attempts to establish equality constraints across time for the exogenous relationships.

Table A.1
Testing equality constraints with nested models

Model	Constraints	χ^2 (d.f.)	Comparison model	Difference χ^2 (d.f.)	Hinders fit
1	None (full model)	978.11 (150)	None	–	
2	All endogenous paths eq across all time periods	1571.60 (190)	1	592.89 (40)	Yes
	Public science–private science relationships				
3	Impact–patent and expenditure–patent paths eq in 1980s (time periods 1–3)	984.96 (154)	1	7.33 (4)	No
4	Impact–patent and expenditure–patent paths eq in 1990s (time periods 4–6)	992.17 (154)	1	14.06 (4)	Yes
5	Impact–patent and expenditure–patent paths eq across time periods 3–4	981.64 (152)	1	3.63 (2)	No
			3	3.32 (2)	No
6	Impact–patent and expenditure–patent paths eq across time periods 4–5	958.82 (152)	1	7.71 (2)	Yes
7	Impact–patent and expenditure–patent paths eq across time periods 5–6	979.21 (152)	1	1.10 (2)	No
8	Impact–patent and expenditure–patent paths eq across time periods 1–4	985.81 (156)	1	7.70 (6)	No
			3	3.32 (2)	No
9	Impact–patent and expenditure–patent paths eq across time periods 1–4 and 5–6	988.51 (158)	1	10.40 (8)	No
			8	2.70 (2)	No
	‘Within realm’ public science relationships				
10	Impact–expenditure and expenditure–impact paths eq across time periods 1–3 (1980s)	985.44 (154)	1	7.33 (4)	No
11	Impact–expenditure and expenditure–impact paths eq across time periods 4–6 (1990s)	981.95 (154)	1	3.44 (4)	No
12	Impact–expenditure and expenditure–impact paths eq across time periods 3–4	979.46 (152)	1	1.82 (2)	No
			10	5.98 (2)	Yes
			11	2.49 (2)	No
13	Impact–expenditure and expenditure–impact paths eq across time periods 1–4	986.15 (156)	1	8.04 (6)	No
			10	3.13 (2)	No
			11	1.35 (2)	No
14	Impact–expenditure and expenditure–impact paths eq across time periods 5–6	979.46 (152)	1	1.35 (2)	No
15	Impact–expenditure and expenditure–impact paths eq across time periods 1–4 and 5–6	987.50 (158)	1	9.39 (8)	No
			13	1.35 (2)	No
	Private science–public science relationships				
16	Patent–impact and patent–expenditure paths eq across time periods 1–3 (1980s)	987.70 (154)	1	9.59 (4)	Yes
17	Patent–impact and patent–expenditure paths eq across time periods 4–6 (1990s)	979.24 (154)	1	1.13 (4)	No
	Combinations of equality constraints				
18	Impact–patent, expenditure–patent, impact–expenditure and expenditure–impact eq across time periods 1–4 and 5–6	997.90 (166)	1	19.79 (16)	No
			15	10.40 (8)	No
			9	9.39 (8)	No
19	Model 18 + patent–impact and patent–expenditure paths eq across time periods 4–6	998.44 (170)	1	20.33 (20)	No
			18	0.54 (4)	No

‘Within realm’ private science paths (patent–patent, assignment–patent) are free in all time periods. All plausible sets of equality constraints hinder overall fit.

model). Notice that the difference χ^2 for a comparison of model two and model one is hugely significant ($\chi^2_{2-1}(40) = 592.89$)[30] suggesting that the additional constraints imposed by model 2 significantly hinder the overall fit of the model. Clearly, there is some change in these endogenous relationships over time.

I identified four sets of coefficients that capture important relationships within and across public and private science. Table A.1 presents models that impose constraints on each of these sets of coefficients individually before turning to models which included equality constraints for more than one set of coefficients. While I will not walk through every step presented in Table A.1 in text considering tests of equality constraints for one set of public–private science relationships will illustrate the process I used to establish my 'final' model.

Consider the section of Table A.1 labeled 'public science–private science relationships'. The models presented here (models 3–9) impose constraints upon the impact → patent and expenditures → patent relationships. Models 3 and 4 test the hypothesis that these relationships are equal in the 1980s and 1990s, respectively. Difference χ^2 tests against model 1 (the full model) indicate that while constraining this set of coefficients to equality across time periods 1–3 (1981–1989) does not hinder model fit relative to the full model (difference $\chi^2_{3-1}(4) = 7.33$, $P > 0.10$) imposing equality constraints across time periods 4–6 (1990–1998) does (difference $\chi^2_{4-1}(4) = 14.06$, $P < 0.01$). Comparing these two models with the full model tells us that the relationships between public and private science remained the same for the period 1981–1989, but varied significantly across the time period 1990–1998.

Model 5 tests the hypothesis that these coefficients are equal across time periods 3 and 4 (1987–1992). The difference χ^2 test suggests that this is the case (difference $\chi^2_{5-1}(2) = 3.63$, $P > 0.10$) as introducing these extra constraints does not hinder overall fit relative to the full model. However, considering model 3 (coefficients equal across 1980s) as a reduced form (more constrained version) of model 5 indicates that the more constrained model 3 is still 'better' fitting (difference $\chi^2_{3-5}(2) = 3.32$, $P > 0.10$). Thus, I turn to model 8 which tests the hypothesis that these coefficients are equal from 1981 to 1992 (time periods 1–4). Table A.1 indicates that this model does not hinder overall relative to either the full model (model 1) or the 'eighties' model (model 3). Hence, I conclude that these coefficients are equal across the first four time periods.

Before turning to a presentation of the final model consider a few more rows of Table A.1. We now 'know' that these public science → private science relationships are constant from 1981 to 1992. Model 6 indicates that this equality does not continue for time periods 4 and 5 (1990–1995). The implication here is that a change in the relationship between public and private science occurred sometime in between 1993 and 1995.

Model 7 indicates that these relationships are constant across time periods 5 and 6 (1993–1998). The implication here is that there was a change in the relationship between public and private science but that this change resulted in a new equilibrium. Model 9 combines the two sets of equality constraints in a 'comprehensive' model of the relationship between public and private science over time. Model 1 does not hinder fit relative to either the full model or model 8 (the previous 'best-fitting' model). Therefore, we can conclude that this model provides the best heuristic for understanding how the relationship between public and private science changed from 1981 to 1998. The implication of model 9 is that these relationships remained constant until 1992 and then changed. The change though seems to represent more an inflection point as the relationships remained constant for the remaining time periods.

I will not detail the process used to establish equality constraints for other coefficient sets. Nevertheless, Table A.1 presents goodness of fit statistics and χ^2 difference tests for each regression 'on the path' to model 19, the best-fitting model presented in the text.

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[30] Recall that a significant χ^2 here indicates that the additional constraints imposed by the reduced model *hinder* model fit. Thus, I take constraints to 'better' model fit when difference χ^2 are *insignificant* at $P > 0.10$. I use the notation χ^2_{x-y} to indicate the full and reduced models whose relationship is indicated by the difference χ^2 test.

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