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Putting university research in context: Assessing alternative measures of production and diffusion at Stanford

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ABSTRACT

Scholars widely acknowledge that university research is critical to innovation and entrepreneurship. Much of the literature on university research, however, evokes a linear model from "science to products" and focuses, therefore, upon a limited set of indicators such as patents and licenses. Such a perspective runs the danger of missing the myriad ways in which science and commerce are intertwined and the myriad ways in which these activities might be assessed. In this paper, I address the question of how different measures reflect different perspectives and biases by investigating the production and diffusion of research associated with one of Stanford University's most prolific interdisciplinary centers, the Center for Computer Research in Music and Acoustics (CCRMA). I draw upon a unique data set that captures activities and engagement surrounding CCRMA for its 30-year history through a wide variety of measures, ranging from publication citations to industrial affiliates to personnel mobility. Employing the analytic categories of "description" and "enactment," and distinguishing between "indicators" and "pathways," I show how different measures reflect different activities and learning processes, and how they dramatically alter perceptions of active individuals, organizational reach, and timing and sequencing of activities. Building on these findings, I present a more complete model of university research production and diffusion, I discuss how alternative measures challenge certain assumptions in the literature, and I suggest concrete policy initiatives to improve our measurement and assessment of university research.

1. Introduction

Although numerous scholars assert that research conducted in universities has a significant influence on innovation, assessing this influence and describing its nature remains a difficult challenge. A good deal of work has focused on measuring the "output" of universities via patents, publications, licenses, and startups, and on attempts to link this "output" to commercial outcomes (e.g., Coupé, 2003; Dechenaux et al., 2008; George, 2005; Jensen and Thursby, 2001; Mowery and Ziedonis, 2002; Shane, 2004; Sine et al., 2003; Thursby and Kemp, 2002; Thursby et al., 2001). Other scholars have focused on alternative measures, including personnel mobility (e.g., Dietz and Bozeman, 2005), consulting relationships (e.g., Jensen et al., 2007; Murray, 2002), hiring of graduate students (e.g., Stephan, 2009), and industrial affiliates programs that provide companies with access to both research and students in exchange for an annual fee (e.g., Shama, 1992; Vlad, 2003). Together, these many studies suggest that the production and diffusion of university research proceeds through a wide variety of different mechanisms (Berkovitz and Feldman, 2006; Perkmann and Walsh, 2007). Unfortunately, very few studies have actually studied multiple mechanisms simultaneously, leaving us, as a result, with far less insight into the *relationships* between these different mechanisms: how do they reflect different aspects of the production and diffusion of knowledge and how might reliance on a particular set of measures bias our assessments of university research?

Initial evidence based on the comparison of just two or three measures suggests that the biases may be considerable. For example, studying the University of California system, Branstetter and Ogura (2005) found that publications far outstrip patents in terms of both production and downstream citations, indicating that reliance on patents alone would dramatically understate the influence of university research. Agrawal and Henderson (2002) found a similar result in their study of MIT, and also demonstrated that the set of firms drawing upon MIT publications was different from the set of firms drawing upon patents. Gittelman (2007) showed that the geographic patterns of university-firm partnerships on publications versus patents differ, with publications reaching "farther." Finally, Nelson (2009) compared patents, publications, and licenses surrounding the Cohen–Boyer recombinant DNA technology. He found that both geographic patterns and the apparent timing of activities differed between measures. This research,

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therefore, suggests that different measures of university research may lead to different conclusions about magnitudes of production and influence, number and demography of active individuals and downstream organizations, and temporal sequencing of activities – in other words, many of the core variables in existing studies. Although studies such as those cited above get at pieces of the puzzle, however, our lack of comprehensive longitudinal data that address both "production" and "reach" of university research has limited our ability to assess the full degree of these biases and their influence on these many variables of interest.

In turn, these more limited approaches to measurement have reflected, at times, a lack of precision in our theoretical descriptions of knowledge creation and diffusion. For example, although scholars have repeatedly challenged the "linear view" in which commercial technologies are the outcome of a path from basic to applied research (e.g., Kline and Rosenberg, 1986; Rosenberg, 2004), the linear view's focus upon patents and licenses as "outcomes" continues to shape the literature on university technology transfer. Similarly, many studies treat different production and diffusion indicators as substitutes, not disentangling the ways in which these indicators may be associated with different kinds of knowledge (e.g., Agrawal and Henderson, 2002; Cohen et al., 2002), or fail to distinguish between indicators and actual pathways (Perkmann and Walsh, 2007).

My goal in this paper is to explore the relationships – both empirical and theoretical – between measures of university research more fully. Thus, I provide a detailed account of the ways in which a multiplicity of measures – including publications and publication citations; patents and patent citations; presentations; industrial affiliate memberships; licenses; employment flows; and, given my unique empirical context, musical compositions – affect our conceptualization and assessment of knowledge creation and diffusion associated with a Stanford University research center. My results suggest that different measures are, indeed, enormously influential: both academic studies and policy initiatives that draw upon limited measures run the danger of reinforcing particularistic conclusions and neglecting the functioning of the overall system. Specifically, I demonstrate how different measures pick up different organizations at different points in time and how no measure, in isolation, provides a representative view of creation and diffusion activities. I also show that measures are not cleanly delineated between commercial and academic spheres. Finally, I tackle issues of temporal sequencing between measures, exploring which measures tend to precede or follow which other ones as an organization engages with Stanford. Throughout this exercise, I highlight several counterintuitive results that question dominant views in the literature and I elaborate upon the analytic categories of "description" and "enactment" to reflect, more generally, on the ways in which these different measures imply different epistemologies of "knowledge" itself.

2. Comparative metrics and competing perspectives surrounding university knowledge flows

A good deal of work demonstrates the economic effects of university research and its importance to innovation (e.g., Adams, 1990; Beise and Stahl, 1999; Berman, 1990; Kenney et al., 2009; Narin et al., 1997; Rosenberg, 1974; Salter and Martin, 2001). For example, the "Yale survey" in the 1980s documented widespread university contributions to the R&D efforts of medium and large U.S. companies (Nelson, 1986). Mansfield, too, conducted a number of studies that linked university research to industrial innovation in various fields, finding that up to 27-percent of innovations by large firms relied upon academic research. (See, for example, Mansfield, 1991, 1995.) As the "data and methods" sections of these papers make clear, however, assessing the production and diffusion of university research remains a difficult task because there is no straightforward and reliable means of identification and measurement.

As a result, a number of scholars have explicitly called for studies on comparative metrics. For example, Foray and Lisoni (2010, p. 309) conclude their review of the literature on university research and public–private interaction by encouraging an expanded range of indicators and an assessment of relationships between them, calling this task "the most important challenge for years to come." Based on a study of university contributions to local innovation in 22 different locations in six countries, Lester (2005, p. 3) concludes, "the 'one-size-fits-all' approach to economic development pursued by so many universities, with its focus on patenting, licensing, and new business formation, should be replaced with a more comprehensive, more differentiated view of the university role. Universities need a stronger awareness of the pathways along which local industries are developing and the innovation processes that are associated with those pathways." Similarly, Feldman and Kogler (2008, p. 446) argue that we should take a more expansive view of university contributions, not reducing universities "to a simple factor of production" but instead recognizing them as a multifaceted "creative force in the economy."

These calls stand in opposition to approaches in the literature – both academic and professional – that focus upon patents, licenses and startups as primary indicators of university contributions to the R&D efforts of other organizations and to innovation generally. A focus on patents, licenses and startups also reflects a particular epistemological perspective on the research process and on the types of knowledge that are relevant to consider. The "linear model" of innovation, typically traced to Vaneevar Bush (1945), posits that work proceeds in a linear fashion from research to development to production and marketing. More generally, it posits that scientific "research" leads to technological "application." Many scholars have documented the distorted reality represented by this model and there is little need to recount their arguments in detail here. (See, for example, Kline and Rosenberg, 1986; Rosenberg, 2004.) For purposes of assessing the production and reach of university R&D, however, it is important to recognize that patents, licenses, and startups capture only the latter "stages" of this linear model.

Indeed, existing studies that have attempted to document and disentangle various measures of university research suggest that dominant approaches to measurement may be problematic. For example, the Carnegie Mellon survey, a follow-on to the Yale survey, asked R&D managers about the relative "importance" of different channels for gaining access to university research. A key result was that publications and informal interactions were of paramount importance, with other channels playing secondary roles. Agrawal and Henderson (2002) asked a similar set of questions, but from the perspective of MIT engineers who make contributions to industry. They found that publications and conferences were of primary importance. Meyer-Krahmer and Schmoch (1998) and Schartinger et al. (2002) conducted comparable surveys of German and Austrian academics, respectively, about the importance of different modes of interaction with industry. They found that informal contacts, collaborative research and contract research played vital roles in facilitating such interactions. Finally, Bekkers and Freitas (2008) surveyed both university- and industry-based researchers about the importance of almost two-dozen different channels through which industry accesses university research. Bekkers and Freitas again confirmed the general importance of publications and they found that characteristics of knowledge, the disciplinary origin of knowledge, the individual characteristics of the respondents, and the characteristics of respondents' workplaces all affected the relative importance of the various channels. (See also Wright et al., 2008.)

These survey-based studies have made important contributions by documenting the presence and importance of different ways by which university research has influence. The focus of these studies, however, has left other important questions unaddressed. First, by comparing "importance" these studies downplay the overlap and interactions between various measures. In fact, they can be taken to imply that various measures are substitutes for one another, rather than exploring the ways in which measures may reflect knowledge differently. Second, these surveys provide us with a sense of how different measures may reflect the *reach* of university research, but not with a complementary view of how these measures reflect research *production*. Third, these surveys focus on the influence of university research on industry, specifically, failing to unpack how other universities and organizations may also pick up this research. Fourth, the cross-sectional design of these surveys does not allow them to assess longitudinal patterns, including the temporal "ordering" of measures and potential changes in relationships over time. Finally, this literature has not presented a comprehensive view of a given academic unit, instead focusing on generalized tendencies and patterns for a broad sample of respondents. As a result, despite repeated calls for comparative metrics surrounding university research, we still lack considerable understanding about the ways in which different measures reflect the production and reach of this activity – and, in turn, underpin particular theoretical perspectives on university research.

3. Data and methods

My interest lies in capturing as complete a picture as possible of university research activities over time. As such, my research design sacrifices breadth for depth. Specifically, I employ a case study methodology in which I investigate activities around one particular university research center. By virtue of aligning faculty and students around a field or topic of mutual interest, the focus on a research center brings interdisciplinary research to the forefront, responding to recent calls in the literature (e.g., Rhoten, 2004), and it places research activities in a common field rather than departmental boundaries as the central focus. For these reasons, an investigation of a center may capture more completely a university's contributions in a field that crosses departmental boundaries.

I chose Stanford as the focal university because it is one of the premier research universities in the world; it is very active in publishing, patenting, and licensing; and it has contributed to substantial commercial activity (Colyvas, 2007; Colyvas and Powell, 2006; Mowery et al., 2001). Within Stanford, I focused on the Center for Computer Research in Music and Acoustics, or CCRMA. CCRMA is a multi-disciplinary facility where composers and researchers work together using computer-based technology both as an artistic medium and as a research tool. Though the Center is based in the music department, affiliated students and faculty stem from music, electrical engineering, computer science, mechanical engineering, and other disciplines. CCRMA's environment, therefore, reflects a growing interest in assessing the influence of universities beyond the common empirical setting of the life sciences (e.g., Crossick, 2006; Hughes et al., 2011). Moreover, the somewhat unusual choice of a center based in a music department marks CCRMA as a strategic setting that may provide insight into mechanisms or processes thus far overlooked in the literature (Eisenhardt, 1989).

As affiliates of an academic center, CCRMA personnel frequently publish and present research. As affiliates of a musical center, CCRMA personnel write and participate in hundreds of compositions and performances. CCRMA's commercial influence, however, also ranks as impressive – even in the highly entrepreneurial environment of Stanford. In fact, CCRMA patents and licenses have generated more than $23 million in licensing revenue. One invention, FM synthesis, was Stanford's most profitable license for years, until it was eclipsed by the Cohen–Boyer recombinant DNA license (Nelson, 2005). Moreover, CCRMA manages a formal industrial affiliates program, which has attracted dozens of member companies and has generated hundreds of thousands of dollars in membership fees alone. The thorough mixing of artistic, basic research and applied research activities means that CCRMA provides a unique lens through which to assess and compare university knowledge creation and diffusion from a broad perspective.

I collected data on this Center from its formal establishment in 1975 through 2005. (The Center's record-keeping procedures changed in 2005, presenting a challenge for data collection from 2005 through 2010. Moreover, since patents take time to issue, the 2005 cutoff permits a reasonable amount of time for initial decisions surrounding patent applications.) My first step was to go through the internal progress reports that are produced by CCRMA on a roughly annual basis. These reports listed publications, lectures, compositions, and performances, along with industrial affiliates, faculty, staff, students, and visitors. I, therefore, compiled my database of publications, presentations, compositions, performances, and industrial affiliates on this basis. I used the personnel lists in these reports as a starting point and refined these lists by consulting annual editions of the Stanford "University Bulletin," which lists course offerings and personnel; by working with the Stanford University Registrar to identify individuals enrolled in various CCRMA courses; and by consulting the annual list of degrees awarded, which includes dissertation topics and academic advisors that could indicate a CCRMA link.

Ultimately, my efforts resulted in the identification of 890 individuals, including faculty, graduate students, undergraduates, and visiting scholars. (Music aficionados might recognize the names of Mickey Hart, Stan Getz and John Cage, amongst the many visiting scholars.) Long-time veterans of the Center validated this list for its completeness. In my analysis, I focused only on graduate students and faculty ($n = 297$), given their (generally) longer association with the Center and the higher quality of the records surrounding their activities. (My inclusion of graduate students is somewhat novel in the university technology transfer setting. See Colyvas and Powell (2009) and Stephan (2009) for other examples.) I refer to these individuals as "core individuals," the "core group," or, adopting the language that CCRMA personnel use to refer to themselves, "CCRMA-lites." Several of these individuals shifted status over time, completing, for example, their doctorate through the Center and later assuming a faculty position. In presenting findings, I also highlight individuals beyond the core who still have a CCRMA affiliation (typically as visiting scholars) and individuals with no formal CCRMA affiliation at all.

I attempted to collect curriculum vitae (CV's) for all core individuals, scouring Internet postings and contacting many individuals via and telephone. (The Stanford Registrar provided contact information.) Ultimately, I obtained 272 CV's, representing about ninety-two percent of the core individuals. Where CVs included information on patents, publications, presentations, compositions, and performances, I used this information to refine my database of these measures.

I obtained licensing data from the Stanford University Office of Technology Licensing (OTL). This office provided me with a list of all invention disclosures and licenses over time, including the inventor(s) of the licensed technology, associated patents, companies that took out a license and their associated dates, and annual licensing revenue. Together, the licensing data and CV's also provide an indicator of spinoffs, or companies that were started by CCRMA personnel to commercialize CCRMA technologies. There is only one spinoff (Staccato Systems) according to this definition, however, so I do not analyze spinoffs separately.

To obtain information on patents, I searched for each core individual in the "inventor" field through the US Patent and Trademark Office (USPTO). This search process resulted in patents by CCRMA personnel both assigned to Stanford (subsequently called "Stanford patents") and not assigned to Stanford (subsequently called "All patents"). To ensure completeness, I conducted another search for patent records assigned to Stanford University in the fields of music, digital audio, computer sound, and related areas. I cross-referenced the resulting patents against my list of CCRMA personnel. In displaying data, I always use the patent application date, not issue date.

As a number of previous studies have demonstrated, both patent citations (Trajtenberg, 1990; Hall et al., 2005) and publication citations (Cole, 2000; Edge, 1979; Hicks, 1995; MacRoberts and MacRoberts, 1989) can provide useful information about work that is related to or builds upon core patents and publications. I obtained patent citation information from the USPTO, identifying a total of 1036 patent citations. Publication citations are tricky in fields such as engineering and music, core disciplines at CCRMA. Unlike the natural sciences and social sciences, which primarily value formal publications and which benefit from complete databases of these publications, publication standards differ in both engineering and music. Specifically, conference publications and white papers are comparable to journal publications in importance, though they are not adequately captured in any formal database. After significant consultation with a number of experts in the field, including senior administrators who determine publication influence for purposes of tenure and promotion, I employed the Google Scholar database to track publication citations. My informants indicated that this database provided the most complete view of a given publication's reach because of the wide range of materials that the database captures. (See also Harzing and van der Wal, 2008; Kulkarni et al., 2009.) As a result of these efforts, my database includes 11,599 publication citations.

Finally, I conducted detailed interviews with 20 personnel who were associated with CCRMA at various points in time. These interviews addressed each person's academic and career history; his or her musical interests and involvement; and his or her research, composition, and performance activities, along with the perceived effect of these activities. Each interview lasted between one hour and four hours, and the total interview transcripts fill more than 300 pages. Although I do not formally analyze these interviews in this paper, I do draw upon insights and anecdotes to illustrate various points.

With the raw data collected, I next engaged in a period of coding, assigning individual identification numbers to each organization picked up via any of the measures. I also researched each organization to determine its type (e.g., "firm" or "university"). Because I am not focused on "independent" versus "dependent" variables, regressions are not an appropriate empirical approach. To provide a better sense of the comparisons between measures, however, I complement graphs and descriptive statistics with correlations and difference tests (*t* tests).

4. Results

4.1. Dimensions of knowledge and measures of production

My research question concerns the ways in which different measures reflect different aspects of the production and diffusion of university research. As a starting point, some further description of the computer music environment will be helpful to the reader. In classical composition, the orchestral instruments are a given set with well-defined physical and acoustical properties. The composition process, therefore, consists of determining which instruments should play what and when. Computer music layers another set of considerations on top of these decisions: in computer music, the means of sound generation, or the "instruments" themselves, also need to be "composed" by writing software code that instructs the computer to generate certain sounds. Because the computer presents nearly unlimited possibilities for synthesizing and transforming sound, the compositional process can be far more complex than in the classical case and typically entails a close connection to electrical engineering, psychoacoustics, and other fields that focus on the manipulation of signals. These close relationships between fields also blur the lines between compositions, performances, scientific research, prototypes, and demonstrations: a sound run through a new signal processing algorithm, for example, may be a proof-of-concept for a new audio tool or it may be the fragment of a new composition. As such, distinctions between types of activity in a computer music research environment can be difficult to distill.

What is easier to distill, at least on the surface, are the different ways in which research activities may be made manifest or appear as an "output." Three of the most common forms of research "output," generally, are publications, presentations, and patents. In musical environments, compositions and performances also play an important role and one that is roughly analogous to the role of prototypes and products in other domains.

Table 1 arrays these "outputs" into different analytic categories. Some outputs, notably publications and presentations, primarily *describe*. Their purpose is to share new insights – techniques, theories, or data – with other researchers, and they accomplish this task through writing and speech. Other outputs, notably compositions and performances (or prototypes and products in other domains), primarily *enact*. They demonstrate the *use* of techniques, theories, or data in the creation of an audio experience that may be shared with researchers and/or lay people. Patents lie between these two categories. The "enablement" requirement for a patent application requires that patents not only "describe," in the same way that a publication might, but also facilitate the "doing" of the description by someone skilled in the art through execution of a process, creation of a product, or some other means.

My use of the categories of "description" and "enactment" mirrors Russell's (1912) description of different ways of "knowing." In *Problems of Philosophy*, Russell distinguished between "knowledge by description" and "knowledge by acquaintance." Although Russell proposed that all knowledge ultimately depends upon experience, he argued that some of that experience may be obtained indirectly through others' descriptions while other experience is directly acquired. Moreover, these types of experience need not overlap; one can directly acquire experience but remain unable to describe it, or one can grasp a description but remain unable to enact it.

To some degree, the categorizations of description and enactment reflect other conceptualizations of different knowledge dimensions. For example, a number of scholars distinguish between "tacit" and "explicit" knowledge (e.g., Collins, 1982; Nelson and Winter, 1982; Nonaka and Takeuchi, 1995; Polanyi, 1967; Tsoukas, 2003). Although the precise meanings of "tacit" and "explicit" are variant across studies, most authors treat "tacit" knowledge as that which has not been "written down" – either due to an inability to do so or a lack of incentives to do so – and "explicit" knowledge as that which *has* been written down (Cowan et al., 2000). Under this conceptualization, the category of "description" obviously reflects explicit knowledge. "Enactment," however, could reflect tacit and/or explicit knowledge, depending upon whether an individual can "describe" what she "enacts." Thus, the typologies are related, but distinct.

Similarly, Arrow (1962) introduced the concept of "learning by doing," by which he meant that learning is the product of experience. Thus, "learning by doing" more closely

Table 1
Categories of output.

	Describe ⟵	⟷	⟶ *Enact*		
	Publications/presentaions	*Patents*	*Compositions/performances*		
What gets revealed	Theory and/or empirical results. Methods in so far as they are necessary to build a compelling case	Methods in enough detail that a person of "ordinary skill in the art" of the field can replicate the invention	Applications of specific signal processing techniques, synthesis techniques, and/or compositional algorithms		
How it gets revealed	Publications: books and journals. Presentations: oral sharing, with visual aids and sound examples	Issued patents (and, in select cases, patent applications)	Performances, recordings, sheet music/tablature, software code		
Primary audience	Other researchers	Legal counsel	Other researchers and lay people		
Authorship	"Authors": All persons who make intellectual contributions to the completion of the research described in the work, including those who provide key data or novel techniques. Authors should be able to independently present and explain the publication in its entirety	"Inventors": All persons who contribute to the claims of a patentable invention and who hold "intellectual domination" over the inventive process, but not those who merely contribute to reducing the invention to practice	"Composers": All persons who work to assemble a particular sequential collection of "organized sounds," but not those who provide raw materials (such as synthesizers) or those who will reinterpret the composition for performance (as in jazz and other improvisational styles)		
	Publications/presentations	*Patents*	*Compositions/performances*	*# in category*	*% of total*
	X			58	19.5%
			X	35	11.8%
		X		1	0.3%
	X		X	23	7.7%
	X	X		21	7.1%
	X	X	X	5	1.7%
				154	51.9%

aligns with "enactment," which also focuses upon experience. Whereas Arrow's focus was upon learning processes and diminishing returns for a practicing individual, however, the distinction between description and enactment also refers to the ways in which outsiders can *observe* a researcher's activities.

What all of these perspectives have in common is an emphasis on the multi-dimensionality of knowledge. In turn, this multidimensionality may be reflected in different indicators or categories. Upon first glance, the categories in Table 1 appear to be relatively distinct. For example, the bottom portion of Table 1 shows how the activities of the 297 faculty and graduate students affiliated with CCRMA are arrayed across these categories. About 20-percent of individuals are active only in "description" through publications and presentations. Another 12-percent are active only in "enactment" through compositions and performances. Just one individual, an adjunct professor with deep industry experience, is active only in patenting. As Table 1 indicates, it is somewhat rare for a single individual to create multiple types of output: only 17-percent of individuals do so. Finally, the majority of CCRMA personnel do not produce any of the "outputs" listed in the table – a first indication that attempts to measure output alone may not capture all relevant activity at a university. (Most of these individuals are graduate students engaged in coursework and research activities that do not result in measured outputs.)

Individual-level correlations between the outputs also suggest that these activities are relatively distinct. For example, the correlation between publications and presentations (both indications of description) is 0.987 and the correlation between compositions and performances (both indications of enactment) is 0.633. The correlation between publications and compositions (opposite ends of the spectrum), however, is just 0.186 and between publications and performances is just 0.169. Similarly, the correlation between patents and compositions is just 0.023 and between patents and performances is just 0.054.

A more nuanced investigation of these activities, however, reveals that too dogmatic an approach to the categories of output at CCRMA risks understating the ways in which these categories of activity are intertwined. For example, composer Mike McNabb reflected on the creative process underlying his CCRMA creations:

> It's really hard to even separate where all the creativity came from. When you talk about one piece of music, any one piece of music, there couldn't help but be at least half a dozen people involved besides the composer because we had to write our own software, the engineers had to build their own equipment, all this stuff. It was like you'd lose track: Did Julius [Smith, an electrical engineer] come up with this special [engineering] thing and we thought, "Well, that's cool. I'm going to use it in a piece." Or the other way around: "I want to do X" and they [people like Julius Smith] would say, "Well one way you could do that is like this" (Personal interview 2009).

McNabb suggests that composition is not a solitary activity, even if a given piece of music lists only a single "composer." (In fact, the statistics bear out his "caution": 98-percent of compositions list a solo composer.)

The program notes that accompany Juan Pampin's 1996 CCRMA composition, *Metal Hurlant*, provide another example of this relationship between the categories in Table 1. These notes read:

> The spectral synthesis and transformations of the sampled percussion instruments were done using ATS, spectral modeling software programmed by me in LISP. All the digital sound processing and synthesis for the piece was performed with CLM, developed at CCRMA by Bill Schottstaedt.

Pampin eventually published the ATS technique, three years later. Two things are notable in the quoted passage. The first is the highly technical language used to describe the composition: this piece is not (only) about imagery, emotion, tension-and-release and other typical features of musical compositions; the research activity, in a sense, *is* the music. Second, the passage clearly highlights the interplay between the realms of description and enactment: building upon Schottstaedt's *description* of CLM, Pampin *enacted* a piece that used a new technique (ATS), which he subsequently *described* for use by other composers and researchers.

To critics of the linear model of innovation, these activities serve as evidence of non-linear dynamics between different aspects of the research process. McNabb's and Pampin's compositional activities suggest that enactment might just as easily precede description (versus follow it) and that applications might *give rise to* attempts to describe rather than *flowing from* lucid descriptions. (In fact, CCRMA professor John Chowning (1983) claimed that one of Stanford's most important and profitable licenses – FM synthesis, which he invented – resulted from late night "fooling around" in search of new sounds for a composition. Chowning then struggled for months to adequately describe his breakthrough in scientific terms.) In turn, since research activities do not follow a single path or present a single "output point," it is critical to capture them in different ways.

Table 2 shows CCRMA's research activity according to different measures. It is immediately apparent that publications, presentations, compositions and performances are the most numerous forms of output. Patents – the hybrid between description and enactment – are relatively rare, though the inclusion of patents by CCRMA personnel that are not assigned to Stanford more than doubles the number. (In their study of nearly 6000 patents with US faculty as inventors, Thursby et al., 2009, also find that many patents by faculty inventors – about one-quarter in their study – are not assigned to the faculty members' universities.) Nevertheless, the tallies in Table 2 show that even though movement between description and enactment may be central to the research process, the measure that captures both activities simultaneously – patents – is somewhat uncommon.

Table 2 also breaks out the activity of graduate students versus faculty. The differences between the total counts and the faculty counts for each measure reveal that not all graduate student activity is due to co-creation activities with faculty. In fact, more than one-quarter of graduate student publications are not co-authored with faculty, almost one-third of Stanford-assigned patents that list a graduate student inventor do not list a faculty inventor, and almost one-half of all patents that list a graduate student inventor do not list a faculty inventor. The independent activities of graduate students are especially evident in compositions and performances. In fact, the graduate student population produced more than twice the number of compositions as the faculty population and exceeded the faculty population in performances.

These findings around graduate student activity are consistent with two complementary explanations: the first explanation reflects – to an extent – Vaneevar Bush's image of the research process. In this case, graduate students who compose pick up the basic tools from others and apply them in new ways. The second account reflects Chowning's experience with FM synthesis: graduate students may be able to *apply* techniques – including new techniques that they develop – before they have the capacity to *describe* them. (Of course, many composers may have no desire to describe novel techniques, period, regardless of their ability.) In either case, tracing graduate student activity proves critical to understanding research at the Center as a whole.

Finally, Fig. 1 arrays these activities over time. Generally speaking, each measure increases over time as the total number of active CCRMA personnel increases. But Fig. 1 reveals more subtle patterns, too. For example, although the first CCRMA patent is in 1975, the Center receives only a handful of patents until the mid-1990s. Thus, patents are not a useful means of tracking activity at CCRMA until many years after its establishment. (Since patents require a blend of description and enactment, it might be expected that patents would take longer to generate. Note that the earliest patents appear before the 1980 Bayh-Dole Act, so patenting activity is not simply the result of legislative changes.) The mid-1990s also exhibit a shift from Stanford-assigned patents to non-Stanford-assigned patents. One interviewee attributed this pattern to a new approach to intellectual property that emerged at CCRMA in the past decade: release "inventions" under an open source model and then rely on profitable professional-education short-courses, improved student job placements, gifts, and other means to realize "value" (Personal interview, 2008). Such commentary highlights how a variety of different factors can influence patenting decisions – including frustrations with OTL practices and changing perspectives on how to obtain value from inventions – and how changes in patenting patterns, therefore, cannot simply be attributed to changes in technical "production."

4.2. Diffusion

Thus far, the data from CCRMA illustrate the multiple ways in which activity is made manifest, the multiple types of personnel engaged in these activities, the relationships between different activities, and the analytic categories of description and enactment. These different analytic categories also are important to assessing the diffusion of work done at CCRMA. In a sense, production and diffusion are two sides of the same coin. In production, the categories of description and enactment refer to the ways in which someone *shows* what he or she has done. In diffusion, description and enactment refer to the ways in which others may *learn about* what someone else has done.

Different diffusion measures may reflect these analytic categories. For example, if subsequent researchers learn how to perform a new technique on the basis of reading a publication that describes this technique, then the diffusion process reflects description. On the other hand, if an organization is able to implement a new technique because it hires a knowledgeable person to carry out the

Table 2
Number of publications, patents, presentations, compositions, and performances.

	Total	Faculty	Graduate students	Max	Min	Mean
Total number of individuals[a]	297	36	272			
Number of:						
Publications	583	484	374	172	0	2.89
Presentations	401	354	312	134	0	2.24
Stanford-assigned patents	34	29	18	13	0	0.16
All patents	76	62	30	19	0	0.31
Compositions	351	107	244	30	0	1.18
Performances	596	288	308	98	0	2.01

[a] Eleven individuals had both graduate student and faculty affiliations at different points in time. In calculating statistics, I counted these individuals as graduate students (faculty) for the years during which they were graduate students (faculty) and for the activities they engaged in during these years.

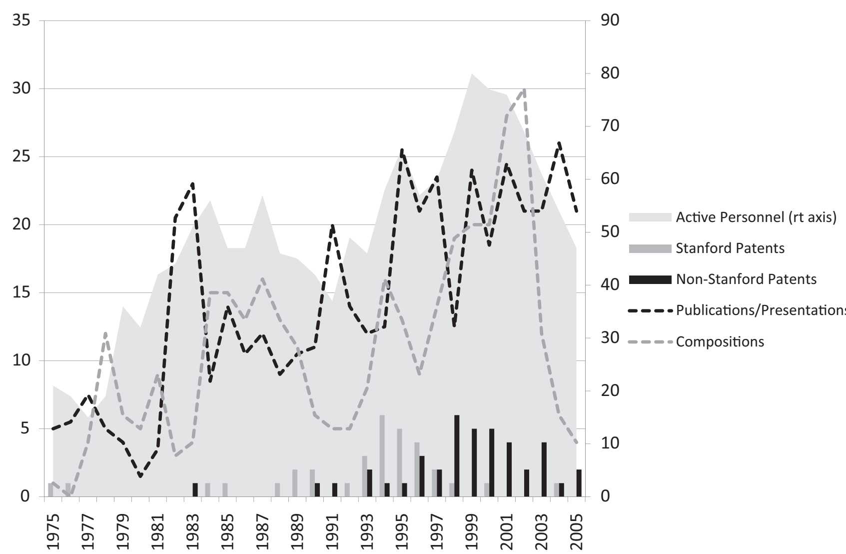

Fig. 1. CCRMA activity over time according to different measures of output (publications and presentations in a given year are highly correlated, so this graph displays the yearly average for the two measures).

technique, the diffusion process reflects enactment. With these distinctions in mind, the column headings of Table 3 array different measures – very coarsely – from description to enactment.

In considering the various measures in Table 3, it also is important to distinguish between diffusion *indicators* and diffusion *pathways* (Perkmann and Walsh, 2007). For example, publication citations provide one indication that the authors of a focal publication have conducted research that is related to a publication that they cite. Thus, the citation serves as an *indicator* that information from the cited publication has diffused to the authors of the citing publication. It is another matter, however, to determine the *pathway* by which these authors gained access to and absorbed this information. It may be that reading this cited publication also served this function, in which case the publication itself

Table 3
Organizations engaging with CCRMA through various mechanisms.

		Description ⟷					*Enactment*
	(All indicators combined)	Publication citers	Stanford-assigned patent citers	All patent citers	Licensees	Industrial affiliates	Hiring organizations
Total unique organizations reflected by indicator	*2057*	*1611*	*112*	*218*	*12*	*39*	*415*
Number of firms (and % of organizations in top row that are firms)	606 (29.5%)	247 (15.3%)	102 (91.1%)	198 (90.8%)	12 (100%)	42 (100%)	249 (60%)
Number of universities (and % of organizations in top row that are universities)	1068 (51.9%)	1040 (64.6%)	7 (6.3%)	15 (6.9%)	0 (0%)	0 (0%)	97 (23.3%)
Number of other organization types (and % of organizations in top row that are others)	383 (18.6%)	324 (20.1%)	3 (2.7%)	5 (2.3%)	0 (0%)	0 (0%)	69 (16.6%)

is a pathway, too. Alternatively, the authors may have learned the information contained in the publication by attending a presentation or by engaging in an informal conversation. In those cases, the citation provides an indication of follow-on activity but the publication is not a pathway in itself. (I use the term "pathways" rather than the more common term in the literature, "channels," in order to elicit imagery of potentially fuzzy boundaries and emerging routes. In this way, I build upon Owen-Smith and Powell's (2004) distinction between closed "pipelines" and open "sprinklers" that diffuse knowledge in different ways.) In other words, to the extent that publication and patent citations pick up knowledge that moves via other pathways, they may overstate the role of publications and patents as pathways in themselves. Previous survey data on the means by which external groups pick up on university research (e.g., Cohen et al., 2002; Agrawal and Henderson, 2002) indicate that both effects – publications/patents as indicators and as indicator-pathways – are probably present.

Some measures, in fact, may serve only as indicators and not as pathways in themselves. For example, the industrial affiliates program provides member firms with advance access to publications, preferential recruitment, and attendance at meetings that include demonstrations and a musical performance. (One firm representative described these performances as "a peek into the real-time and real-world applications of some of the research," suggesting that performances convey meaningful information through the process of enactment.) Thus, the industrial affiliates program is effective in diffusion by facilitating activity along other pathways rather than as a pathway in itself.

Moreover, some pathways can be impossible to capture completely and on a longitudinal basis. For example, although conference presentations can be a meaningful pathway for diffusion, attendance at these presentations and "absorption" by these attendees can be very challenging to assess. Similarly, informal conversations can be a highly influential – but very difficult to capture – pathway. Measurement and data gathering difficulties thus decree that the pathways portrayed in Table 3 are necessarily incomplete.

Finally, it is important to note that a *potential* pathway is not necessarily a *utilized* pathway. For example, though hiring a knowledgeable graduate may be a potential means for a firm to gain access to new knowledge, it is far from a guarantee. For this reason, counting organizations that travel a particular path – to follow the analogy – may not yield an accurate count of organizations that learn something as a result of this journey.

All of these observations bolster the case for comparing multiple measures of activity: if different measures reflect different diffusion processes, then a comparison between measures provides an improved sense of each one independently and of the overall diffusion process. These comparisons are particularly useful towards understanding the relative magnitude, organizational demography, overlap, and sequencing between different pathways, as I show in the subsections below.

4.2.1. Magnitude and demography of influence

To begin, Table 3 shows various pathways and the number of organizations "reached" via each pathway. Publication-citing organizations make up nearly 80-percent of the total population of follow-on organizations. Employment flows indicate the next largest number of organizations reached. Since these flows overwhelmingly reflect the movement of graduate students beyond CCRMA (into their first post-graduate job and subsequent positions), the magnitude of organizations reached via employment reinforces the importance of graduate students as a knowledge diffusion pathway. By contrast, patent citations pick up between five and ten percent of follow-on organizations, while licenses and industrial affiliates reflect just a handful of organizations.

The next three rows of Table 3 indicate the demography of organizations reached via each pathway. As the table illustrates, some pathways are tied to certain kinds of organizations. For example, licensees and industrial affiliates are all firms. Other pathways are more likely to reflect certain types of organizations. For example, most patent citers (about 90-percent) are firms, whereas most publication citers (about 85-percent) are universities and other non-commercial organizations. Given the large number of publication citers, however, the set of firms proves interesting: 247 firms cite CCRMA publications and only 49 of these same firms cite CCRMA patents. Publication citations, therefore, pick up more firms than do patent citations (247 versus 198) and they pick up a largely non-overlapping set of firms. These results indicate that even if interest is limited to firms' use of university research, publication citations remain a critical measurement.

4.2.2. Overlap between measures

To assess the overlap between measures, Tables 4 and 5 present cross-tabulations. In Table 4, the entries reflect the number of individual organizations picked up by both the measure in the row and the measure in the column. In Table 5, the cross-tabulations are displayed as a percentage, indicating the proportion of total organizations picked up by the measure in a given row that are also picked up by the measure in a given column.

The tables show a considerable lack of overlap between measures. For example, the vast majority of Stanford-assigned patent-citing firms (95 of 102) do not hold a license from Stanford. In fact, of the top ten patent-citing organizations, only one is a licensee (Yamaha Corporation, of Japan). Overall, ninety-four percent of patent-citing organizations have no licensing relationship with the Stanford OTL! When the patent-citing group is expanded to consider non-Stanford-assigned patents, the same patterns remain. Thus, there is still only one licensee (Yamaha) amongst the top ten citers and ninety-six percent of patent-citing organizations (210 of 218) have no relationship to the Stanford OTL! These results provide strong evidence that licenses do not provide a complete indication of subsequent enactment or "use" and that studies which focus upon technology licensing offices as primary gateways for university research are likely to miss the vast majority of activity.

About 40 percent of industrial affiliates cite Stanford-assigned CCRMA patents, while about 60 percent do not. If patent citations are the evidence of subsequent enactment, these results would indicate that the industrial affiliates program is only marginally effective. The cross-tabulations, however, reveal other patterns. For example, there is more overlap between industrial affiliates and publication citers than between industrial affiliates and patent citers. Since all industrial affiliates are firms, this overlap reinforces the fact that more firms pick up on publications than patents and it suggests that publications convey commercially important knowledge not contained in CCRMA-lites' patents. At the same time, no measure captures more than 57-percent of industrial affiliates, indicating that program membership picks up connections missed by other measures. Finally, the number of industrial affiliates versus licensees (42 versus 12) and the fact that more industrial affiliates than licensees cite CCRMA patents (17 versus 7) together indicate that "industrial affiliate programs" may be a more fruitful place than "technology transfer offices" to search for firms picking up on university research.

Tables 4 and 5 also show some degree of overlap between hiring organizations and those organizations picked up via other measures. Thus, one-quarter of organizations that cite CCRMA patents also have an employment tie to CCRMA, as do about one-half of licensees and industrial affiliates (Table 5, last column). But, the most description-oriented pathway – publications – shows less than eight-percent overlap with the hiring set. This

Table 4
Overlap between different measures of engagement.

	Stanford-assigned patent citations	All patent citations	Publication citations	Licensees	Industrial affiliates	Hiring organizations
Stanford-assigned patent citations	112					
All patent citations	112	218				
Publication citations	43	68	1611			
Licensees	7	8	4	12		
Industrial affiliates	17	20	24	6	42	
Hiring organizations	28	39	124	6	22	415

Numbers in cells indicate the number of individual organizations picked up by both the measure in the row and the measure in the column. For example, 43 organizations cite both publications and Stanford-assigned patents. The diagonal entries indicate the total number of organizations picked up by a measure.

finding reinforces the distinction between description and enactment, with description-oriented pathways reaching a greater number of organizations and a different set of organizations than enactment-oriented pathways.

4.2.3. *Temporal patterns*

Different measures also reveal different temporal patterns. Fig. 2 illustrates activity over time. The figure shows that CCRMA reaches an increasing number of organizations each year. (These counts are annual, not cumulative.) Since publications reach the largest number of organizations overall (Table 3), their general pattern tends to be mirrored in the pattern for all active organizations. Publication citations also show a fast rate of growth compared to other measures. Employment, for example, also reaches a large number of organizations, but the growth in organizations reached via employment ties is linear. These differences result from the nature of description versus enactment as diffusion mechanisms. Diffusion via description is highly scalable since multiple parties can read (or listen to) a single researcher's description simultaneously. The hands-on nature of enactment, however, limits its scalability; to increase the growth rate of diffusion via employment, it is necessary to increase either the total number of people in the system or the rate of turnover.

As noted, a number of organizations are reflected in multiple measures of diffusion. (See Tables 4 and 5.) For these cases, Table 6 shows which measure picks up a given organization first. Several notable patterns are apparent in the data. First, in the vast majority of cases in which an organization cites both a Stanford-assigned patent and a non-Stanford-assigned patent, its first citation is to a Stanford-assigned patent. This finding indicates that Stanford-assigned intellectual property may be a gateway into further research activities that move beyond the Stanford intellectual property umbrella.

In overlap cases between patents on one hand and publications, licenses, and industrial affiliates on the other hand, the proportion of "firsts" is fairly evenly split; thus, there is almost equal probability that the patent citation or the publication-citation/license/affiliate-membership will come first. This finding is particularly notable for the case of licenses and industrial affiliates, since it indicates that patent citations do not necessarily follow (in a temporal sense) from signing a license or joining the industrial affiliates program. In fact, the opposite case, in which an organization first cites CCRMA patents and then later signs on as a licensee or an industrial affiliate, is just as likely. In the case of licenses, this finding indicates that, for many organizations, it is only after they are already making use of Stanford intellectual property in their own patent applications (which, in turn, arise only after a period of research) that the organizations sign a license. Thus, the formal relationship with the OTL emerges relatively late and the license is more reflective of intellectual property considerations than it is of a burgeoning research relationship. Although this result could be unique to CCRMA since CCRMA engaged in some of the earliest patenting at Stanford (just as the OTL was formed), this pattern also holds later in time, thus suggesting a more general tendency. In fact, multiple interviewees described cases in which already-established research collaborations "had to [later] get the sign-off from the OTL once we hit a certain stage" (Personal interview, 2008).

In overlap cases between hiring organizations and patent citers, the data give a stronger sense of a dominant sequence: in three-quarters of the cases, organizations hired CCRMA personnel before ever citing CCRMA patents. This finding implies that patent citations may, in part, function as a lagged indication of personnel flows. In other words, the hiring of a former CCRMA-lite may have been the actual pathway, with the patent citation serving as a lagged indicator of diffusion but not as a pathway in itself.

Finally, the data show that in about three-quarters of overlap cases, an organization has a relationship with CCRMA through a hiring relationship before it becomes an industrial affiliate. Although one benefit of the industrial affiliates program is that it provides special recruiting access to students, the data show that companies already have employment relationships in most cases.

All of these results challenge a (strictly) linear view in which research – and diffusion – proceeds from publications to patents to licenses and, more generally, from description to enactment. Instead, the data provide examples of numerous pathways and sequences. Fig. 3 presents these relationships in the form of a network. Each node, therefore, represents a diffusion measure. The size of each node is scaled to the overall number of downstream organizations picked up by the measure. A line between two

Table 5
Overlap between measures, expressed as a percentage.

	Stanford-assigned patent citations	All patent citations	Publication citations	Licensees	Industrial affiliates	Hiring organizations
Stanford-assigned patent citations	100.0%	100.0%	38.4%	6.3%	15.2%	25.0%
All patent citations	51.4%	100.0%	31.2%	3.7%	9.2%	17.9%
Publication citations	2.7%	4.2%	100.0%	0.2%	1.5%	7.7%
Licensees	58.3%	66.7%	33.3%	100.0%	50.0%	50.0%
Industrial affiliates	40.5%	47.6%	57.1%	14.3%	100.0%	52.4%
Hiring organizations	6.7%	9.4%	29.9%	1.4%	5.3%	100.0%

Numbers in cells reflect the percentage of all organizations picked up by the measure in the row that are also picked up by the measure in the column. For example, 2.7% of organizations picked up by publication citations are also picked up by Stanford-assigned patent citations.

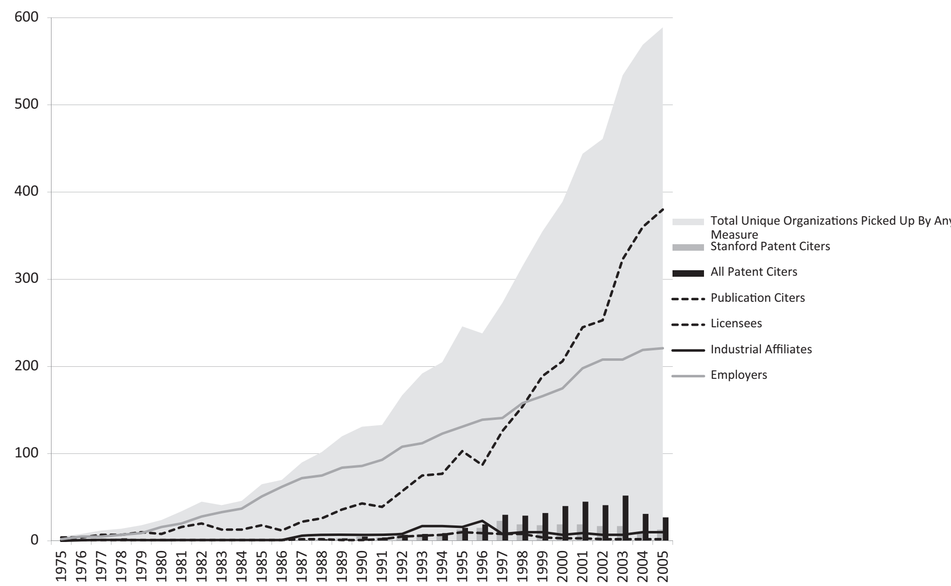

Fig. 2. Total unique organizations picked up by each measure, by year.

Table 6
Sequencing of activity for overlap cases.

	Stanford-assigned patent citations	All patent citations	Publication citations	Licensees	Industrial affiliates
All patent citations	7 (6%)–105 (94%)				
Publication citations	21 (49%)–22 (51%)	37 (54%)–31 (46%)			
Licensees	3 (43%)–4 (57%)	4 (50%)–4 (50%)	4 (100%)–0 (0%)		
Industrial affiliates	9 (53%)–8 (47%)	11 (55%)–9 (45%)	12 (50%)–12 (50%)	2 (33%)–4 (66%)	
Hiring organizations	21 (75%)–7 (25%)	29 (74%)–10 (26%)	66 (54%)–58 (46%)	3 (50%)–3 (50%)	16 (73%)–6 (27%)

When an individual organization is picked up via multiple measures (Table 4), the first number/percentage reflects cases in which the row entry picks up the organization first, while the second number/percentage reflects cases in which the column entry picks up the organization first. For example, in the lower-right cell, there were 22 organizations that both hire a CCRMA-lite and have a relationship as an industrial affiliate. In 16 of 22 cases (73-percent), the organization first hired a CCRMA-lite and later joined the industrial affiliates program. In 6 of 22 cases (27-percent), the organization first joined the industrial affiliates program and later hired a CCRMA-lite.

nodes indicates that an individual organization is reflected in each connected measure, with thicker lines indicating more organizations employing the combination. Finally, the arrowheads indicate the temporal sequencing of shared measures (e.g., which measure appeared first when a given organization is reflected by multiple measures).

The sequence implied by a linear view of engagement is certainly present, with a line running from publications (on the left)

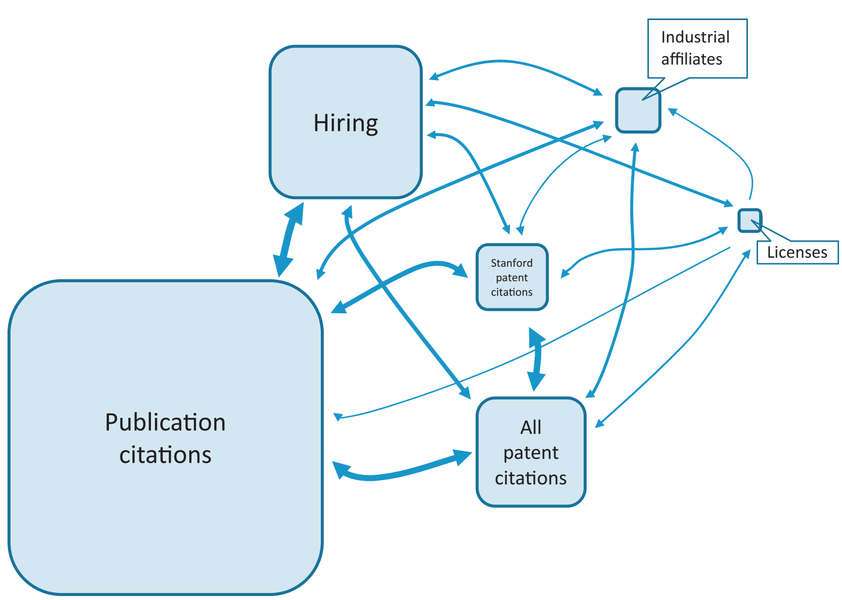

Fig. 3. Relationships between diffusion measures.

to Stanford patents (in the middle), and from Stanford patents to licenses (on the right). More remarkable, however, are the number and direction of other lines in the diagram. As in production of work at CCRMA, the sequence from enactment to description – rather than just description to enactment – appears common in diffusion, too. In fact, nearly every sequence is represented, and the diagram as a whole illustrates a world in which organizations pick up on CCRMA research through a wide variety of pathways employed in a number of different sequences.

5. Discussion and conclusion

5.1. Summary of results

In 1945, Vaneevar Bush made an impassioned plea for the Federal funding of university research in the U.S., which culminated in the establishment of the U.S. National Science Foundation. Numerous scholars have reinforced Bush's case over time, highlighting the important role that university research plays in innovation, economic growth, and entrepreneurship in countries around the world (e.g., Jaffe, 1989; Mansfield, 1995; Mowery and Sampat, 2005; Salter and Martin, 2001). Bush's vision and many subsequent attempts to quantify university influence also left us with a unfortunate perspective, however, which has focused attention on a few select measures that, in isolation, may not adequately or impartially represent the activity within a university and its influence beyond a university.

In this study, I take a novel approach to the question by conducting a detailed examination of one university research center's activities and effects. I began by introducing the analytic categories of description and enactment to distinguish between different ways in which we may observe a researcher's activity and different ways in which other researchers may pick up on this activity. Employing this framework alongside the examination of different measures, I demonstrated that graduate students are responsible for a significant proportion of university outputs, including patents, and that many of their activities proceed independently of faculty. I also demonstrated that publications are far more common than patents (e.g., Branstetter and Ogura, 2005), that publications and patents appear to be complements (Azoulay et al., 2007; Breschi et al., 2007; Markiewicz and Di Minin, 2008), and that nearly one-half of patents with active CCRMA personnel are not assigned to Stanford. Amongst this music-oriented group, performances and compositions (reflecting enactment) and presentations (reflecting description) are also some of the most numerous forms of output.

Turning my attention from measures of creation to measures of diffusion, I began by distinguishing between indicators and pathways. I then showed how publication citations and, to a lesser extent, personnel flows reflect many, many more organizations than other measures. In fact, I found that publication citations pick up more firms than do patent citations and that the two sets of firms are largely non-overlapping. Examining licensees and industrial affiliates, I found that the vast majority of patent-citing firms did not hold a license from the OTL and that far more firms engaged with CCRMA through the CCRMA-managed industrial affiliates program than as an OTL-managed licensee, signaling a difference between relationships managed at the university level versus the departmental level. Industrial affiliates also picked up more patents than did licensees. In turn, however, industrial affiliates cited publications more than they cited patents, again highlighting the important role of publications in the commercial development of university technologies. Finally, I showed the considerable overlap between organizations that hire CCRMA-lites and those picked up as publication/patent citers, licensees, and/or industrial affiliates.

My last set of analyses considered the temporal sequencing of different mechanisms of engagement. I found that licensing and industrial affiliate relationships were just as likely to emerge after an organization had already cited CCRMA patents as they were to precede them. This finding casts doubt on a model in which a technology transfer office brokers relationships with external organizations that eventually result in patent citations. I also found that in 75-percent of cases, an employment relationship preceded an organization's first patent citation, indicating that patent citations may be acting as a proxy for personnel flows in many cases. In these cases, patent citations will provide a lagged signal of university influence and should be recognized as an indicator, not a pathway. A similar pattern held between employment ties and industrial affiliate memberships, such that most organizations first hired a CCRMA-lite and later joined the affiliates program. The network image in Fig. 3, which summarized many of these findings, indicated nonetheless that nearly every sequence of engagement was present in the data.

Together, this thorough examination of CCRMA provides us with a much richer sense of the diversity of ways in which a university research group "creates knowledge," of the ways in which these activities have influence, and of the relative magnitudes and biases of particular measures. The data also highlight how science and commerce are intertwined in myriad ways. Since each indicator picks up unique activity, reflecting description and enactment in different ways, and since nearly every sequence of engagement is present in the data (Fig. 3), this examination of CCRMA serves to disentangle – theoretically and empirically – the rich web of activities taking place in universities and the ways in which they connect externally.

At the same time, these results encourage a context-sensitive approach to the study of university research. Music and digital media remain relatively understudied arenas of university innovation – despite the growing economic and cultural importance of these industries (as witnessed, for example, by the resurgence of Apple). Unfortunately, we have little comparative evidence on the ways in which measures and processes differ across fields. Obviously, certain measures such as compositions and performances are somewhat unique to a musical setting. In other settings, however, prototypes or demonstrations might serve similar roles. The general lesson to be drawn from CCRMA, of course, is that different activities, processes, and connections are reflected in different measures. At the same time, it is far more informative to look at connections across measures and sequences between activities than it is to limit our analyses to a small set of presumed "outputs."

5.2. Theoretical contributions and implications for research

These results, therefore, bolster studies that question a linear model in which research proceeds from basic to applied to commercialization. Although a growing number of studies make this point through detailed examinations of production processes (e.g., Godin, 2006; Kline and Rosenberg, 1986; Stokes, 1997), none have called out the continued influence of this perspective on our treatment of university knowledge flows. In turn, if research "spills out" at many different points in the research process, then those markers typically associated with the "end point" of the linear model – patents and licenses – are not the only place to look for universities' influence. These results thus allow us to extend critiques of the linear model into the arena of university technology transfer, specifically, and to consider the ways in which adherence to this model distorts assessments of university influence.

In turn, the demonstration of the relative magnitudes, biases, and relationships between different measures raises questions for the academic literature on university knowledge flows. For example, the data on graduate student activities suggest that studies that examine only faculty members may dramatically understate the influence of universities, missing up to 70-percent of activity depending on the researcher's interest. Although faculty are undoubtedly important, the role of graduate students has remained relatively unexplored in studies of university research production and diffusion (Stephan, 2009). Nelson and Byers (2005) argue, in fact, that graduate students are uniquely positioned to commercialize university research since they are not tied to (semi-) permanent university positions. Similarly, studies that focus on patents but consider only those patents assigned to the university may miss up to one-half of patents involving university personnel. These results suggest, therefore, that studies focused on patents must take care to investigate what this measure actually reflects. For example, the data on patent and employment overlap indicate that patent citations in many cases serve as lagged indicators of employment flows and should not necessarily be interpreted as diffusion mechanisms in themselves.

The differences between measures displayed in Tables 2 and 3 indicate, in fact, that reliance on certain measures can drastically under-report both production and reach. Moreover, the activities captured may be biased in terms of organizational demography and timing. Given the literature's focus on questions such as university-firm relations (e.g., Perkmann and Walsh, 2007) and the role of universities in the emergence of new technologies (e.g., Bozeman et al., 2007), these demonstrated effects cut to the heart of contemporary research on university knowledge flows by raising questions about the empirical basis of these studies.

Finally, this study demonstrates the relationship between different measures and different epistemological stances on "knowledge." Specifically, I introduced the categories of description and enactment, distinguishing between these different methods of description and learning and linking different measures to these categories. I also demonstrated that measures may reflect these categories as distinct even as qualitative accounts reflect significant blending and co-mingling between activities captured via different measures. This perspective, therefore, contrasts with other approaches in the literature on multiple "channels" that treat these channels as substitutes and that compare their relative "importance" (e.g., Agrawal and Henderson, 2002; Cohen et al., 2002) or that focus primarily upon the overlap between indicators (e.g., Hagedoorn and Cloodt, 2003). Instead, my findings encourage studies of university knowledge flows to better account for "what," exactly, particular measures reflect and how these measures relate to one another. The goal in such an approach is not to minimize variance between measures, but rather to exploit this variance in order to gain further insights into production and diffusion processes.

5.3. Policy implications

These findings also hold important implications for policy makers and practitioners. First, the many views of activity at CCMRA highlight the enormous challenge in attempting to assess the effect of university research and they suggest specific steps that universities, organizations such as the Association of University Technology Managers (AUTM), and government agencies may take towards improving our measurement of university research. Specifically, CCRMA is somewhat unique amongst university research groups in that it maintained detailed records on a variety of metrics over a long time period. If future work is to embrace a more expansive view of knowledge creation and diffusion, universities themselves might do more to encourage the maintenance of such detailed and systematic records. Organizations like AUTM can also play a role. Indeed, AUTM is to be commended for its work in gathering patenting and licensing data across numerous universities and for making the results of these surveys available to researchers. At the same time, as many researchers lament, the AUTM data provide no correlation between disclosures, patents, and licenses, such that one cannot tell what, if anything, has happened to a given disclosure or patent. As a result, the data provide only a very coarse estimate of the total activity flowing through a university licensing office, without the more detailed linkages that could better inform policy.

Of course, given the importance of university research to innovation and economic growth as a whole, the onus for improved assessment should not lie with individual universities or groups like AUTM alone. Rather, governments have critical roles to play in improving measurement of university activity and influence. Specifically, governments can sponsor efforts to expand the range of innovation indicators captured by various agencies, as the ongoing U.S. NSF project on science policy metrics is exploring (Lane, 2010). Identification of existing indicators also could be improved, facilitating, for example, more accurate matching of both individual and organizational names in the patent data and census data, along with more obvious linkages between patents on one hand and specific agency grants on the other hand. Such efforts should be coordinated internationally, too, to better facilitate important comparisons of policies and institutional environments.

Finally, for policy analysts and university administrators alike, this study's results point to a general challenge in emphasizing particular metrics. As Blau (1954) noted in his study of employment agencies, metrics not only *reflect* activity, but also *shape* it in important ways. In the realm of innovation indicators, Freeman and Soete (2009) remind us of "Goodhart's Law": once something is declared to be an important measure, people will immediately reduce the correlation between the desired good and the measure by taking actions to inflate the measure artificially. Thus, even if executed licenses or patent citations are primary desired outcomes, emphasizing these metrics alone is unlikely to spur effective commercialization since organizations can take actions to inflate theses measures without a concomitant increase in innovation. In fact, the intertwined and multifaceted view of the research and diffusion process highlighted in this paper points to a more austere warning: efforts to "grow outputs" that are focused on only a few indicators may actually be detrimental to innovation if they shift rewards and resources away from crucial, but underappreciated, activities.

Universities, of course, are incredibly – and wonderfully – diverse environments, and this diversity is reflected in the very wide range of activities and subjects pursued under their umbrellas. Perhaps, we should not be surprised if, as a result, assessing the production and diffusion of university research demands an equally diverse set of measures.

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