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Technology transfer and public policy: a review of research and theory

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Abstract

My purpose is to review, synthesize and criticize the voluminous, multidisciplinary literature on technology transfer. To reduce the literature to manageable proportions, I focus chiefly (not exclusively) on *recent literature on domestic technology transfer from universities and government laboratories*. I begin by examining a set of fundamental conceptual issues, especially the ways in which the analytical ambiguities surrounding technology transfer concepts affect research and theory. My literature review follows and I emphasize technology transfer's impact and effectiveness. I employ a ''Contingent Effectiveness Model of Technology Transfer'' to organize the literature. As the model's name implies, it assumes that technology effectiveness can take a variety of forms. In addition to examining the more traditional effectiveness criteria-those rooted in market impacts- the model considers a number of alternative effectiveness criteria, including political effectiveness, capacity-building. © 2000 Elsevier Science B.V. All rights reserved.

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> In general, the process of commercializing intellectual property is very complex, highly risky, takes a long time, cost much more than you think it will, and usually fails. (US Congress, Committee on Science and Technology, 1985, p. 12)

1. Introduction

In the study of technology transfer, the neophyte and the veteran researcher are easily distinguished. The neophyte is the one who is not confused. Anyone studying technology transfer understands just how complicated it can be. First, putting a boundary on ''the technology'' is not so easy. Second, outlining the technology transfer process is virtually impossible because there are so many concurrent processes. Third, measuring the impacts of transferred technology challenges scholars and evaluators, requiring them to reach deep down into their research technique kit bag. Why? The impacts are usually numerous and they are almost always difficult to separate from other parts of organizational life. In many instances, determining the meaning of technology transfer ''effectiveness'' proves daunting. (Indeed, much of my analysis assumes multiple, sometimes conflicting, definitions of technology transfer effectiveness.)

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The challenges notwithstanding, the topic ''technology transfer'' has spurred great interest among academic researchers and policy-makers. Among some indicators of technology transfer's ascension are the following.

- Since 1980, the US Congress has passed no less than eight major policy initiatives dealing with technology transfer and means of promoting it; similar trends have occurred in other nations (Lederman, 1994; Fujisue, 1998; Licht and Nerlinger, 1998).
- At least one journal, the *Journal of Technology Transfer*, is devoted exclusively to ''technology transfer'' and several professional organizations include technology transfer in their mission statement.
- ''Technology transfer agent'' is a job title now listed in many government employee and civil service manuals all around the world.
- During the past 2 decades, the terms ''technology transfer'' or ''technology diffusion'' have appeared in the titles of hundreds of articles and books. [1]

The latter indicator of technology transfer's importance (or perhaps fashionableness) seems to me especially relevant to the task of reviewing literature. When hundreds of different voices are heard and scores of definitions provided, a concept begins to lose meaning. One means of dealing with the cacophony is to parse the technology transfer literature. *This review focuses chiefly on recent literature on domestic technology transfer from universities and government laboratories*. There is a prodigious body of work on transfer within the private sector, from one company to the next. Most of this work is not considered here. Albert Link's paper in this volume considers much of that literature and other overviews are available (e.g., Zhao and Reisman, 1992). Similarly, there is a venerable tradition of research in international technology transfer (e.g., Robinson, 1988). That body of work also receives little attention here.

My approach focuses on technology transfer's impact and effectiveness. A ''Contingent Effectiveness Model of technology transfer'' is developed subsequently and used in organizing the literature. The model considers a number of determinants of effectiveness, including various characteristics of the technology, the transfer agent and the technology recipient. But the most important point of the model (as its name implies) is that technology transfer effectiveness can have several meanings, including market impacts, political impacts, impacts on personnel involved and impacts on resources available for other purposes and other scientific and technical objectives.

Before reviewing findings in the literature, a couple of tasks help clear the way. Section 2 considers fundamental conceptual issues, focusing on the ways in which the analytical ambiguities surrounding technology transfer concepts affect research and theory. Then, we turn to brief consideration of the differences in institutional context between the two types of technology producers and transfer agents examined here — universities and government laboratories.

2. Conceptual issues in technology transfer

2.1. Defining technology

In many instances, definitional controversies can be quickly resolved by simply relying on dictionaries. This is not one of those instances. The unabridged Webster's (1989, p. 1872) offers just three definitions of technology, none of which sets definitional controversies to rest. Technology is defined as: (1) the science or study of the practical industrial arts; (2) the terms used in a science, technical terminology; (3) applied science. None of the major works on technology transfer uses any of these definitions of technology. Works on technology transfer generally focus on technology as an entity, not a study and certainly not any specific applied science. The most common view of technology is ''a tool'', and then discussions proceed as to just what type of tool qualifies as technology.

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[1] A search on the topic ''technology transfer'' in the Georgia Tech card catalog, focusing on the years 1975–1999, found 579 technology transfer books and monographs published in the period. An on-line search of academic journals focusing on articles with ''technology transfer'' found 1032 published articles during the period 1990–1999. These are crude indices of interest in technology transfer but, nonetheless, underscore the difficulties of making sense of rapidly growing, highly fragmented literature.

Sahal (1981; 1982) is one of the few theorists who has written about alternative concepts of technology and the confusion owing to poorly specified concepts. He refers to technology as ''configurations'', observing that the transfer object, the ''technology'', must rely on a subjectively determined but specifiable set of processes and products. Simply focusing on the product is not sufficient to the study of transfer and diffusion of technology; it is not merely the product that is transferred but also knowledge of its use and application. This approach resolves a major analytical problem: the difference between technology and knowledge transfer. By Sahal's concept the two are not separable — when a technological product is transferred or diffused, the knowledge upon which its composition is based is also diffused. Without the knowledge base the physical entity cannot be put to use. Thus, the knowledge base is inherent, not ancillary.

2.2. Demarcating the transfer object

Whether technology transfer or knowledge transfer, a perpetual challenge is demarcating the transfer object from its environment. Sahal (1981) uses the example of the Stirling engine. Which specific components and which specific characteristics of its use does one consider when specifying the transfer object? Which specific characteristics demarcate it from all other engine technologies? Sometimes this question is easily answered, sometimes not. For technologies that are highly standardized and delivered in a standard socio-technical package, demarcation is not an important conceptual problem. But for technologies that exist in considerable variation, one faces a challenging task of demarcation (Argote et al., 1990; Lam, 1997). Since relatively few technologies are transferred in invariant form, failure to specify the transfer object can lead to considerable confusion. The confusion often is greatest when there is primarily a social aspect to the technology. Arguably, a social technology is never transferred in invariant form. Transferring a budget and accounting innovation or a new social learning technology implies an important demarcation problem. If the technology transfer fails, is it because a different social technology has been transferred or is it because the technology has been less successful in a different setting?

2.3. Stability and transformation rules

Even after agreement on the demarcation of a technology, the technology may change. Indeed, it is likely to change since many technologies are not stable. When has it changed so much that it is a different technology? In some cases a technology is changed because there is an active attempt by its users or creators to change it. In other cases, the technology is changed by either by characteristics of its use or by changes in the physical and social setting within which the technology exists. That is, the technology is adapted through personalized application (Jervis, 1975), based on some combination of unique needs (Klein and Crandall, 1991) and tacit knowledge (Teese, 1977; Howells, 1996). When the functions and application environment changes, does that affect the meaning of the technology or its transfer?

2.4. Defining technology transfer

Once one deals with the difficulties of defining the technology, defining technology *transfer* presents a bit less of a challenge. Nevertheless, there are many uses of the term ''technology transfer''. Roessner (in press) (p. 1), in his overview of technology transfer, defines the concept as ''the movement of know-how, technical knowledge, or technology from one organizational setting to another''. But after providing this straightforward definition, he goes on to note:

> The term has been used to describe and analyze an astonishingly wide range of organizational and institutional interactions involving some form of technology-related exchange. 'Sources' of technology have included private firms, government agencies, government laboratories, universities, nonprofit research organizations, and even entire nations; 'users' have included schools, police and fire departments, small businesses, legislatures, cities, states and nations. . . . Within single organizations such as large, research-intensive private firms, technology transfer has been used to describe the processes by which ideas, proofs-of-concept, and prototypes move from research-related to production-related phases of product development.

As Zhao and Reisman (1992) note in their review of the technology transfer literature, the definition of technology transfer differs substantially from one discipline to the next. They observe that economists (Arrow, 1969; Johnson, 1970; Dosi, 1988) tend to define technology on the basis of the properties of generic knowledge, focusing particularly on variables that relate to production and design. According to Zhao and Reisman (1992) (p. 14), sociologists (Rogers, 1962; Rogers and Shoemaker, 1971) tend to link technology transfer to innovation and to view technology, including social technology, as ‘‘a design for instrumental action that reduces the uncertainty of cause–effect relationships involved in achieving a desired outcome’’. Anthropologists (Foster, 1962; Service, 1971; Merrill, 1972) tend to view technology transfer broadly within the context of cultural change and the ways in which technology affects change.

In sheer volume, the greatest number of technology transfer-related publications has been produced by management scholars. According to Zhao and Reisman, those from the business disciplines tend to focus on stages of technology transfer, particularly relating design and production stages, as well as sales, to transfer (e.g., Teese, 1976; Lake, 1979). Management researchers are more likely than others to focus on intrasector transfer (Rabino, 1989; Chiesa and Manzini, 1996) and on the relation of technology transfer to strategy (Laamanen and Autio, 1996; Lambe and Spekman, 1997). Recently, researchers (Hagedoorn, 1990, 1995; Niosi, 1994; Niosi and Bergeron, 1992; Mowery et al., 1996; Kingsley and Klein, 1998) have focused extensively on alliances among firms and how alliances pertain to the development and transfer of technology.

In sum, technology transfer is defined in many different ways, according to the discipline of the research, but also according to the purpose of the research. While the search for a canonical definition is futile, attention to definitions promotes some understanding of differences among research traditions.

Much about the course of technology transfer research and theory can be understood in terms of attempts to deal with thorny conceptual problems. A very different sort of influence on research trends is public policies and other social changes affecting the environment for technology transfer. The most obvious example, at least in the US, is the extent to which the growth curve for research on technology transfer has closely mimicked the growth curve for policies and government activities related to technology transfer. This policy context is reviewed in Section 3.

3. Institutional change and the technology transfer research agenda

Before about 1980, the vast majority of research on technology transfer focused on cross-national technology transfer, especially the transfer of technology from industrialized nations to less developed nations. While cross-national technology transfer continues to receive a great deal of interest both with respect to public policy (Correa, 1994) and academic research (Reddy and Zhao, 1990; Grupp, 1994), the 1980s witnessed many new thrusts in domestic technology transfer policy and an accompanying emphasis among researchers.

In the early 1980s, the research agenda began to shift to domestic technology transfer, particularly in works by US authors. In the US, the 1980s and early 1990s bore witness to vast changes in public policy pertaining to technology transfer and ‘‘competitiveness’’ (Rahm, 1992; Papadakis, 1994). But the 1980s trend for a more aggressive role for government in supporting technology transfer was not confined to the US (e.g., Irvine et al., 1981; Crow and Nath, 1990, 1992; Fujisue, 1998). Major social and political changes inevitably attract the attention of researchers and the study of technology transfer is no exception.

3.1. Politics and technology policy paradigms

Elsewhere (Bozeman, 1994; Crow and Bozeman, 1998), I describe the history of US technology policy in terms of three competing paradigms, the market failure paradigm, the mission paradigm, and the cooperative technology paradigm. (See Rothwell and Dodgson (1992) for a description of the evolution of technology policy paradigms in Europe). Since this approach helps succinctly to organize the vast sweep of technology policy history, a modified version of the conceptual device is used here. Table 1 summa-

Table 1
Three competing technology policy models

Market failure	Mission	Cooperative technology
Core assumptions		
(1) Markets are the most efficient allocator of information and technology.	(1) The government role should be closely tied to authorized programmatic missions of agencies.	(1) Markets are not always the most efficient route to innovation and economic growth.
(2) Government laboratory role limited to market failures such as extensive externalities; high transaction costs; and information distortions. Small, mission domain, chiefly in defense. Universities provided basic research, in line with private sector under-supply due to market failure (inability to appropriate directly the results of basic research).	(2) Government research and development (R&D) is limited to missions of agencies, but not confined to defense. University R&D supports traditional roles of land grant universities such agricultural or engineering extension, manufacturing assistance and contract research for defense or energy research.	(2) Global economy requires more centralized planning and broader support for civilian technology development.
(3) Innovation flows from and to private sector, minimal university or government role.	(3) Government should not compete with private sector in innovation and technology. But a government or university R&D role is a complement.	(3) Government laboratories and universities can play a role in developing technology, especially pre-competitive technology, for use in the private sector.
Peak influence		
Highly influential during all periods	1945–1965; 1992–present.	1992–1994
Policy examples		
De-regulation; contraction of government role; R&D tax credits; capital gains tax roll back. Little or no need for federal laboratories except in defense support.	Creation of energy policy R&D, agricultural labs, and other such broad mission frameworks.	Expansion of federal laboratory roles and university role in technology transfer and cooperative research and other technology-based economic development programs.
Theoretical roots		
Neo-classical economics	Traditional liberal governance with broad definition of government role.	Industrial policy theory, regional economic development theory.

rizes the three technology policy paradigms. My focus is chiefly on the cooperative technology paradigm as it relates closely to technology transfer.

3.1.1. The market failure technology policy paradigm

The market failure technology paradigm is based on familiar premises: the free market is the most efficient allocator of goods and services and, left to its own devices, an unfettered market will lead to optimal rates of science production, technical change and economic growth. The market failure policy paradigm recognizes that there may be a role for government in science and technology policy when there are clear externalities (i.e., that benefits cannot be captured in the market); when transactions costs are extremely high; and when information is unavailable or there are distortion in information so that market signals are not clear.

According to the market failure paradigm, the government role in technology transfer should chiefly be limited to removing barriers to the free market, through appropriate intellectual property policies, free trade agreements, neutral impact taxation, and limited regulation of enterprise. The chief role of universities is not as a broker of technology or a commercial competitor but an educator and a provider of public domain research. As Rosenberg and Nelson (1994) and others (Geiger, 1986, 1993; Lee, 1998) point out, US universities were, throughout most of their history, practical in orientation, emphasizing engineering and technical craft more than basic research. Following World War II, US universities evolved into the top tier of the world's basic science performers. Universities are now viewed as the chief source of basic research and, indeed, market failure theory suggests that this is as it should be.

3.1.2. The mission technology paradigm

In the US, the mission paradigm has for many years influenced the government technology policy role, including early efforts in agriculture research and extension and setting of standards and intellectual property policy (Dupree, 1986), but the mission paradigm has been most influential in the post-World War II period (Reingold, 1994). The mission paradigm assumes that the government should perform R&D in service of well-specified missions in which there is a national interest not easily served by private R&D. In the US, the most important element of the mission technology policy paradigm is defense and national security-related R&D, but such missions as energy production and conservation, medicine and public health, space, and agriculture have expanded the role of universities and federal laboratories.

The mission paradigm has long been prominent in most industrialized nations (Allen et al., 1978; Lederman, 1994), including even those, such as Japan (Chiang, 1995), that allegedly are quite different in structure (Crow and Nath, 1990; Bozeman and Pandey, 1994). In the mission paradigm, there is, in addition to a definition of the roles of government R&D performers, a widespread recognition of the unique ability of government to marshal resources and to influence events in such a way as to foster technology development and innovation (Chiang, 1991).

3.1.3. The cooperative technology policy paradigm

The cooperative technology policy paradigm features an active role for government actors and universities in technology development and transfer. According to this paradigm, government's role can be as a research performer, including supplying applied research and technology to industry, or as a broker, developing policies affecting industrial technology development and innovation. Thus, the cooperative technology paradigm is an umbrella term for a set of values emphasizing cooperation among sectors (Larsen and Wigand, 1987; Wigand and Frankwick, 1989) — industry, government, and university — and cooperation among rival firms in development of pre-competitive technologies and ‘‘infratechnologies’’ (Link and Tassey, 1987).

In the US, the cooperative technology paradigm has been extremely controversial in that it goes against the strong market ethos that has permeated not only science and technology policy but most realms of public policy. Like the market failure paradigm, cooperative technology has established its own myths, many of them not yet having been tested by research (Geisler, 1997). While the waters are clouded by bold claims for inter-sector partnerships (e.g., Kearns, 1990; Wilde and Cooper, 1990; Schriesheim, 1994), there is also some evidence to support the notion that inter-sector cooperation often succeeds in creating technology-based value (e.g., Brown et al., 1991; Brown and Wilson, 1992; Bozeman et al., 1995; Spann et al., 1995). Perhaps the strongest intellectual rationale for the cooperative technology paradigm is provided by Kash and Rycroft (Kash and Rycroft, 1994; Rycroft and Kash, 1994). They take the controversial (at least in the US) position that a government technology planning and coordinating role can augment productivity and innovation.

In the US, the 1980s and early 1990s was a period in which the dominant market failure paradigm received its strongest challenge. Challenges to market failure thinking included policies changing patent policy to expand the use of government technology (Patent and Trademark Laws Amendment, 1980), relaxing anti-trust regulations, promoting cooperative R&D (Bayh–Dole; National Cooperative Research Act of 1984), developing cooperative research centers and consortia (Devine et al., 1987; Berman, 1990; Dill, 1990; Smilor and Gibson, 1991); and altering guidelines for disposition of government-owned intellectual property (Bagur and Guissinger, 1987; Gillespie, 1988; Powell and Owen-Smith, 1998).

The cooperative technology development policies having attracted the most attention are those pertaining to the use of federal laboratories as a partner in the commercialization of technology (Rahm et al., 1988; US General Accounting Office, 1989; Kelley, 1997). A variety of public policies (reviewed below) freed the US federal laboratories from previous limitations on the disposition of federally produced or sponsored intellectual property and actively encouraged technology transfer through cooperative R&D agreements (CRADAs).

At the same time as federal policy was shifting to a cooperative technology paradigm, the US state governments and intergovernmental policies were emphasizing technology-based economic development programs (Roessner and Wise, 1994; Storper, 1995) through manufacturing extension (Wyckoff and Tornatzky, 1988; Shapira, 1990) and university–industry partnerships (Rosenberg and Nelson, 1994; Kingsley and Farmer, 1997), science parks (Felsenstein, 1994; Brown, 1999) and technology incubators (Mian, 1994).

The legislative initiatives enabling the cooperative technology policy paradigm have been reviewed thoroughly elsewhere (Bozeman and Coker, 1992; Hill and Roessner, 1997; Crow and Bozeman, 1998; Roessner, in press). Lee (1994) (pp. 263–264) catalogs most of the legislation from the cooperative technology policy paradigm. Taken together, these policy changes fueled interest in inter-sector technology development and transfer policies and created a cottage industry among academic researchers interested in explaining and evaluating the policies and their impacts. Table 2, adapted from Lee (1994) and updated, presents major technology policy legislation.

As Table 2 shows, the most significant US public policies for domestic technology transfer were promulgated during the 1980s. However, the study of government-sponsored domestic technology transfer certainly began long before. Previous studies focused on such policies as the spin-off activities of NASA (e.g., Rosenbloom, 1965; Doctors, 1969, 1971; Chakrabarti and Rubenstein, 1975) and technology transfer from the federal government to state and local governments (e.g., Feller and Menzel, 1977; Lambright, 1979). Before the 1980s many other nations were already actively pursuing a domestic cooperative technology policy and researchers documented and evaluated those efforts (e.g., Allen et al., 1978; Gummett and Gibbons, 1978). But the deluge of US federal legislation during the 1980s and early 1990s provided a major spur to technology transfer research in the US and elsewhere.

The cooperative technology policies described in this section depend greatly on universities and government laboratories. The logic is simple: universities and government labs make, industry takes. To be sure, many policies involve co-production of technology and various forms of collaboration between industry and either government or universities. But the central point of cooperative technology policies is clear: putting universities and government laboratories to greater use as progenitors of technology and applied science. The logic of this objective depends, then, on the suitability of universities and government laboratories to the task. Section 4 examines briefly the respective institutional contexts of univer-

Table 2
Major technology policy legislation of the 1980s and 1990s

Bayh–Dole Act of 1980 (PL 96-517): permits universities and small business to obtain title to inventions funded by the federal government so as to license inventions.
Stevenson–Wydler Technology Innovation Act (1980) (PL 96-480): requires federal laboratories to establish technology transfer offices and to set aside funds for technology transfer.
Small Business Innovation Development Act of 1982 (PL 97-219): requires federal agencies to provide special set aside funds for small business R&D.
Cooperative Research Act of 1984 (PL 98-462): eliminates treble damage of anti-trust so that firms, universities and federal laboratories can engage in joint pre-competitive R&D.
Federal Technology Transfer Act (1986) (PL 99-502): authorizes national laboratories to enter into cooperative R&D agreements (CRADAs) and negotiate licensing agreements.
Executive Orders 12591 and 1218 of 1987: promotes commercialization of federal technology.
Omnibus Trade and Competitiveness Act of 1988 (PL 100-418): renames the National Bureau of Standards as the National Institute for Standards and Technology and expands its mission; establishes centers for transferring manufacturing technology.
National Competitiveness Technology Transfer Act of 1989 (PL 101-189): extends CRADA authority to all federal laboratories, including weapons labs.
Defense Authorization Act of 1991 (PL 101-510): establishes model programs for linking defense laboratories with state and local government and small businesses; provides Defense Manufacturing Technology Plan.
Defense Authorization Act of 1993 (PL 103-160): renames the Defense Advanced Research Projects Administration and authorizes dual-use technology programs for industrial application.

sity and government laboratory research and the comparative advantage of the settings.

4. Universities and government laboratories as a setting for technology transfer

4.1. Universities and government laboratories as technology transfer settings: fundamentally alike in all unimportant respects?

Anyone who has spent time in both universities and government laboratories need not be told that the two are in some ways vastly different from one another. Moreover, in today's political climate universities and government laboratories often find themselves direct competitors for resources (National Academy of Sciences, 1995).

In our study of US R&D laboratories, Michael Crow and I (Crow and Bozeman, 1998) provide data contrasting university and government laboratories. The statistical evidence shows that many of the differences between university and government laboratories are differences of degree. In a study of more than 1200 university, industry and government laboratories, we found that 23% of university laboratories view technology development as a major mission, compared to 51% of government labs. Whereas 70% of university laboratories view basic research as a major mission, 42% of government laboratories do (and only 11% of industry labs). The findings for technology transfer to industrial organizations indicated that 40% of university laboratories were involved in technology transfer and 52% of government laboratories. University and government laboratories differed as well in the composition of their technical work, but, again, not so dramatically as one might suppose. University laboratories devoted 44% of their activity to publishing scientific research, compared to 36% in government labs. Each lab type devoted only 2% of its activities to production of patents and licenses and each devoted 8% to production of algorithms. In both universities and government laboratories (and industry laboratories as well) the dominant technical disciplines are not the basic research mainstays physics and chemistry, but medicine and engineering.

Government laboratories and universities share important features. In both university and the larger government laboratories, the reward system is largely based on scientific publications, not commercial activity. Some federal laboratories have something equivalent to an academic tenure process. While in the past, MS-level scientists were much more common in the federal laboratories than in universities (where they are virtually non-existent), today a PhD is a de facto requirement for employment in many federal lab positions. Federal laboratory and university scientists read the same journals, attend the same conferences and are generally well aware of one another's work. Nobel laureates can be found in relative abundance in both settings. Generally, federal laboratories are more likely to be managed hierarchically and on a departmental basis and to have more bureaucratic procedures and red tape (Crow and Bozeman, 1989; Bozeman and Crow, 1991b), but the work itself (if not the administration) tends to be quite similar.

Both universities and government laboratories have greatly stepped up their commercial activities during the past 15 years. Cohen et al. (1998) provide some recent data on universities' interaction with industry (see also Cohen et al., 1993). In the brief period between 1991 and 1993, gross royalties from 101 universities' licenses grew from US$163 million to US$318 million. In 1980, only 25 US universities had technology transfer offices, but by 1990 there were more than 200.

The share of university R&D supported by industry has increased. In 1970, only 2.6% of university R&D was supported by industry, but by 1990 that percentage was up to 6.9, much of it to the new university–industry R&D centers created during the past 2 decades. As of 1990, there were an estimated 1056 university–industry R&D centers (Cohen et al., 1993). Cohen et al. attribute this increase in university–industry R&D to a number of factors including provisions of the Bayh–Dole Act permitting universities to obtain patent rights from federally sponsored research, a decline in government funding for university R&D, and government programs creating such industry–university centers as the NSF Science and Technology Centers and Engineering Research Centers.

One straightforward index of industry–university technical activity is the amount of university R&D funded by government. While the federal government continues to provide the vast majority of R&D funding for universities, during the period 1991 to 1997, industry support rose 20% to US$1.05 billion, representing 6.5% of all basic research expenditures (National Science Board, 1998b). Industry–university collaboration increases are also indicated by the fact that 6% of all academic publications in 1995 were with industry scientists. This figure represents about 10,000 scientific and technical articles, a significant percentage of the 439,000 world-wide publications (National Science Board, 1998a). Perhaps the most noteworthy indicator of academic commercial activity is patenting and licensing. In 1982, US universities filed 458 patents, 70% by the largest 100 universities. By 1995, 1860 patents were filed by universities and the percentage by the largest 100 had gone down to 50%, indicating greater depth and breadth of patenting activities.

The commercial activities of government laboratories have grown similarly during the same period. While CRADAs are not an entirely valid measure of commercial activity or value, they do indicate technical linkages. Between 1992 and 1995, 1553 CRADAs were registered between the Department of Energy laboratories and other partners, mostly industrial firms. The Department of Defense labs, with 1001 CRADAs were also quite active (National Science Board, 1998a). Interestingly, the lowest numbers for all laboratories were in 1995, signaling a declining interest in CRADAs, perhaps as an indirect result of the election of a majority Republican Congress, largely unsympathetic to the cooperative technology policy paradigm.

4.2. University vs. federal laboratory: comparative advantage

The major comparative advantage of federal laboratories is their ability to perform interdisciplinary team research, always difficult at universities, organized as they are on the same disciplinary lines as they have been for the past 50 years. A second major advantage of the federal laboratories, especially the national labs, is that extremely expensive, often unique, scientific equipment and facilities are located on their premises. The ''user facilities'' at federal laboratories are designed explicitly to share resources and these user facilities can be an important instrument for technology transfer (Bozeman et al., 1999).

The most obvious advantage of universities over federal laboratories is a vitally important one — students. The presence of students makes a remarkable difference in the output, culture and utility of research. In recommending that federal funding for science and technology give strongest emphasis to academic institutions, the Committee on Criteria for Federal Support of Research and Development of the National Academy of Sciences (1995) (p. 20) concluded that university R&D funding supports production of ''well prepared scientists and engineers who not only will be the next generation of faculty, but who will also work productively in, and transfer technology to, industry and government''.

In our intensive case studies of basic research projects (Bozeman et al., 1999), the results for government laboratories and universities were remarkably similar *except* for the value added of students. Students are (sometimes to their disappointment) a reservoir of cheap labor supporting university research, bartering their below market wage rate for training. More important for present purposes is that students are a means of technology transfer (through postgraduate job placements) and they often provide enduring links as the social glue holding together many faculty scientists and the companies they work with. Roessner et al. (1998) found that the single most important benefit to industry from participation in the NSF Engineering Research Centers, according to the industrial participants themselves, is the ability to hire ERC students and graduates. In some cases, the vast benefits accruing from students are enjoyed by government laboratories, but chiefly at such institutions as Lawrence Berkeley Lab or Ames Laboratory, those actually located on university campuses. We shall return to this issue subsequently in a discussion of the role of ''scientific and technical human capital'' (Bozeman and Rogers, 1998a,b; Bozeman et al., forthcoming).

5. Contingent Effectiveness: a model for organizing the technology transfer literature

During the past 10 years, the research on university and government technology transfer has grown enormously. To organize the literature and the

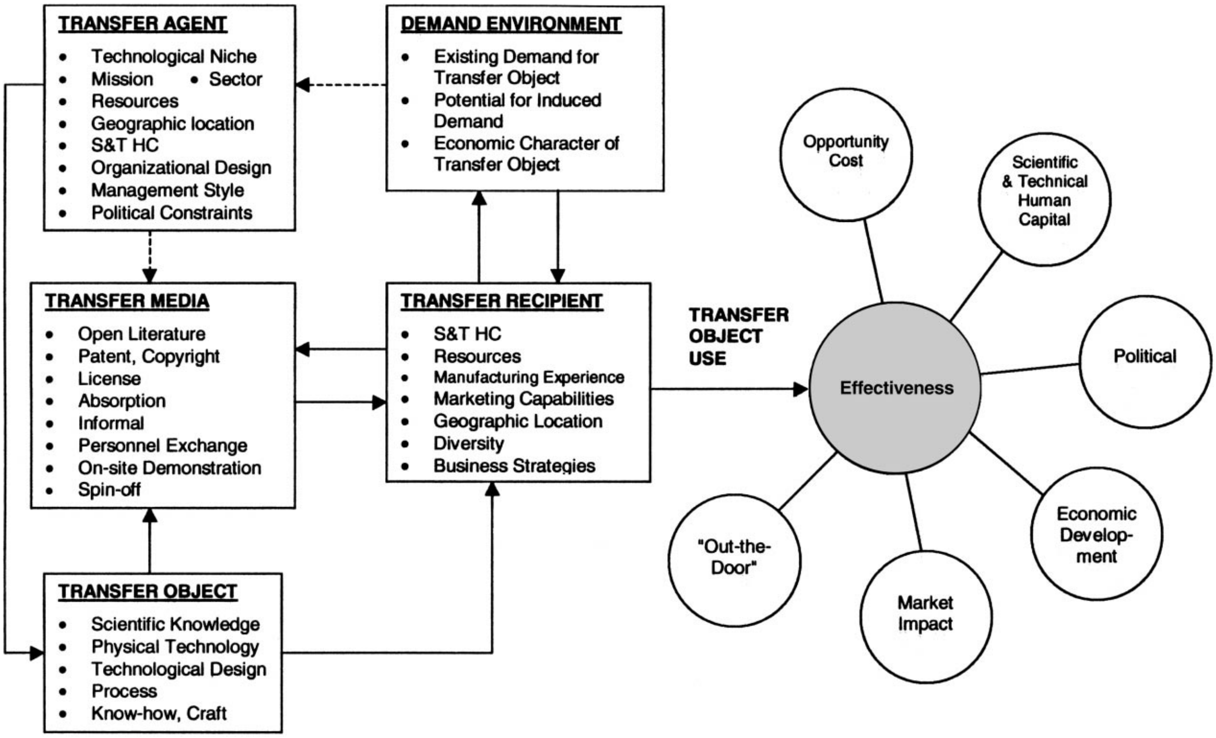

Fig. 1. Contingent Effectiveness Model of technology transfer.

Table 3
Dimensions of the Contingent Effectiveness Model

Dimension	Focus	Examples
Transfer agent	The institution or organization seeking to transfer the technology.	Government agency, university, private firm, characteristics of the setting, its culture, organization, personnel.
Transfer medium	The vehicle, formal or informal by which the technology is transferred.	License, copyright, CRADA, person-to-person, formal literature.
Transfer object	The content and form of what is transferred, the transfer entity.	Scientific knowledge, technological device, process, know-how, and specific characteristics of each.
Transfer recipient	The organization or institution receiving the transfer object.	Firm, agency, organization, consumer, informal group, institution and associated characteristics.
Demand environment	Factors (market and non-market) pertaining to the need for the transferred object.	Price for technology, substitutability, relation to technologies now used, subsidy, market shelters.

propositions flowing from it, I provide a ‘‘Contingent Effectiveness Technology Transfer Model’’. [2] The model focuses on effectiveness, a perspective well-matched to a literature so often motivated by the search for ‘‘what works’’.

Fig. 1 presents the elements of the Contingent Effectiveness Model of technology transfer. The Contingent Effectiveness Model draws its name from its assumption that parties to technology transfer have multiple goals and effectiveness criteria. The model includes five broad dimensions determine effectiveness: (1) characteristics of the transfer agent, (2) characteristics of the transfer media, (3) characteristics of the transfer object, (4) the demand environment, and (5) characteristics of the transfer recipient. These dimensions are not entirely exhaustive but are broad enough to include most of the variables examined in studies of university and government technology transfer activities. The arrows in the model indicate relations among the dimensions (broken lines indicate weaker links). To put it simply, the model says that the impacts of technology transfer can be understood in terms of who is doing the transfer, how they are doing it, what is being transferred and to whom.

Table 3 elaborates the dimensions of the Contingent Effectiveness Model and Table 4 describes briefly the effectiveness criteria associated with the model. The major assumption of the Contingent Effectiveness Model is no single notion of effectiveness makes much sense, either theoretically or practically. Unfortunately, many studies of technology transfer never make clear what is meant by effectiveness and seem simply to assume that we all hold some unspecified unitary concept of effectiveness (see Rahm and Hansen, 1998, for an elaboration of this point). This assumption is wrong, as we have shown with both statistical (e.g., Bozeman and Coker, 1992; Coursey and Bozeman, 1992; Bozeman, 1994) and case study (e.g., Bozeman and Fellows, 1988; Bozeman et al., 1999) evidence. In recognition of the importance of effectiveness issues, Section 7 is devoted entirely to understanding technology transfer research and theory in terms of very different, even contradictory, effectiveness concepts.

6. Technology transfer literature: a focus on *determinants* of effectiveness

Given the vastness of the technology transfer literature, even the subset of the literature on university and government technology transfer, my review

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[2] The simple organizing scheme was first developed by Bozeman and Fellows (1988) in an attempt to understand the very different outcomes from a set of technology transfer case studies; it was then tested in a set of research studies (Bozeman and Coker, 1992; Bozeman and Crow, 1991a); Michael Crow and I (Crow and Bozeman, 1998) modified the model and used it to a series of research findings from the National Comparative Research and Development Project. This version of the model is, nonetheless, considerably different than its progenitors, having included additional effectiveness categories.

Table 4
Technology transfer effectiveness criteria

Effectiveness criterion	Focus	Relation to research and practice
‘‘Out-the-Door’’	Based on the fact that one organization has received the technology provided by another, no consideration of its impact.	Extremely common in practice, uncommon as an evaluation measure (except in studies measuring degree of participation in technology transfer).
Market Impact	Has the transfer resulted in a commercial impact, a product, profit or market share change?	Pervasive in both practice and research.
Economic Development	Similar to Market Impact but gauges effects on a regional or national economy rather than a single firm or industry.	Pervasive in both practice and research.
Political Reward	Based on the expectation of political reward (e.g., increased funding) flowing from participation in technology transfer.	Pervasive in practice, rarely examined in research.
Opportunity Costs	Examines not only alternative uses of resources but also possible impacts on other (than technology transfer) missions of the transfer agent or recipient.	A concern among practitioners, rarely examined except in formal benefit–cost studies.
Scientific and Technical Human Capital	Considers the impacts of technology transfer on the enhanced scientific and technical skills, technically-relevant social capital, and infrastructures (e.g., networks, users groups) supporting scientific and technical work.	A concern among practitioners, rarely examined in research.

emphasizes not only particularly important findings but also more recent ones. A further limitation — I focus chiefly on empirical research. Readers interested in intrasector, cross-national, conceptual and older literature should consult general reviews of the literature (e.g., Godkin, 1988; Zhao and Reisman, 1992; Geisler, 1993).

The review is organized by dimensions of the Contingent Effectiveness Model. We begin with research on the characteristics of the technology transfer agent, an issue already introduced in Section 5 pertaining to the institutional contexts of universities and government laboratories.

6.1. Characteristics of the transfer agent

A broad issue in characteristics of the transfer agent is the nature of the institution, its history and culture. Indeed, a good proportion of the work on technology transfer deals with just this one question: ''How does the institutional culture of the university (government laboratory) affect its ability to conduct technology transfer?''

Much of the research on university technology transfer focuses on the culture of the university (e.g. Daniels, 1994; Larsen and Wigand, 1987), including resistance of university faculty to some of the prerequisites of proprietary work. Some studies suggest organizational and professional changes enabling closer academic and industry collaboration. Etzkowitz (1994; 1998) has conducted interview-based studies of the nature of the entrepreneurial academic scientists and the institutional culture that gives rise to ''the capitalization of knowledge''. Ertkowitz finds considerable change in the norms of academic science, resulting in an environment much more conducive to industrially relevant work. To a large extent this is due to new forms of linkage arising from externalization of industry research and various cooperative R&D organizations which have proliferated in the past decade.

A somewhat less sanguine view is taken by Lee (1996), who conducted field interviews with faculty and administrators involved in university–industry relations and a representative survey of university faculty. He received responses from 986 faculty representing all major disciplines and a variety of university types. He found strongest support for a faculty role in technology-based regional economic development and increasing faculty interaction with industry scientists. Faculty were much less enthusiastic about business partnerships with industry and a more market-driven university. Lee points out that university commercial activities usually do not have high yield (Feller, 1990) and often involve considerable risks. This echoes the conclusion of Rosenberg and Nelson (1994) (p. 346) that it is ''ill-advised to try to get university researchers to work on specific practical problems of industry...(u)niversity researchers are almost always insufficiently versed in the particulars of specific product markets to make good decisions about appropriate tradeoffs''. Lee (1996) concludes that the chief concern of his academic respondents is a ''Faustian bargain'', trading income and research support for new work norms that threaten academic integrity. Despite reservations, however, most academic respondents are willing to cross cultures and have greater, if cautious, collaboration with industry.

The motives of academics involved in technology transfer were examined by Rahm (1994) in her study of researchers in the top 100 research universities. She received responses from more than 1000 academic researchers and then distinguished between 254 ''university-bound researchers'', those not participating in technology transfer, and 759 ''spanning researchers''. The spanning researchers tend to initiate communications with firms and are much more likely to have informal links with firms. Seventy-five percent of the spanning researchers engage in consulting (26% university-bound) and 80% of the spanning researchers have students in industry whom the contact regularly (18% for university-bound). Similarly, spanners are more likely to participate in research consortia, extension services, incubators, and cooperative R&D.

Slaughter and Rhoades (1996) focused on the university as a setting for cooperative technology development, drawing a link between competitiveness policies of the last 2 decades and changes in academic science and technology. They examined aggregate time series data and concluded that the external policy environment of cooperative technology and competitiveness is having effects on the structure of academic work, including salary distributions by field and faculty research choices and rewards. They suggest that the new policies are divisive for university scientists, opening up new and deep fissures between sciences and engineering and arts and letters.

Rahm et al. (1988) examined university and government laboratories' technology transfer activities and the extent to which the characteristics of the lab could explain participation in technology transfer. Focusing on questionnaire and telephone survey data from 665 respondents they found that the composition of university and government laboratories' R&D affects their technology transfer participation. Both universities and government laboratories emphasizing basic research as a mission are less likely to be involved in technology transfer (with the negative relationship being much more pronounced among government labs). Those involved in technology development are considerably more likely to be engaged in technology transfer but, again, the finding is much stronger for government labs.

For both settings, the strongest predictor of technology transfer participation was having a diversity of research missions. Those who were narrowly focused, regardless of the nature of the focus, were less likely to be engaged in technology transfer than those laboratories with diverse, multiple missions. For government laboratories, a focus on scientific articles was associated negatively with technology transfer participation (no association was found for university labs).

In a later study based on survey data from 189 government laboratories, Bozeman and Coker (1992) found that three different types of effectiveness related to the attributes of the transfer agent, but in different ways. Number of licenses related chiefly to the size of the lab; getting technologies out the door was best explained in terms of the missions of the laboratories and the composition of their R&D; Market Impact, measured in terms of commercialized technology, was best explained by research diversity and degree of commercial orientation of the lab.

The geographic location of the transfer agent may in some instances be important. While one study found very little relationship between nearly 100 government laboratories' geographic location and their success in technology transfer (Coker, 1994), geography may determine destiny in some important ways. For example, a study of federal laboratories in New Mexico (Radosevich, 1995) found a significant shortage of risk capital. Arguably, geographic location is in that case only indirectly related to technology transfer success, but as a general factor may take on some importance.

6.2. Characteristics of the transfer media

One transfer medium recently prominent in the literature, because recently prominent in public policy, is the CRADA. Since the passage of the Federal Technology Transfer Act, the US multiprogram, national laboratories, among others, have been permitted to develop cooperative research agreements and to negotiate licenses. In 1989, the National Competitiveness Technology Transfer Act extended that authority to the weapons laboratories. One of the latest efforts to study the effects of CRADAs is the study of Ham and Mowery (1998) of Lawrence Livermore National Laboratory CRADAs. Ham and Mowery focused on five CRADA cases based on diverse technologies, including, for example, improving the recording density of disk drive heads and commercializing high-precision amplifiers. The projects had considerable range in size (less than US$250,000 to more than US$20 million) and varied from 14 to 48 months in duration. In assessing the success (Market Impact criteria) of the CRADA projects, Ham and Mowery found several transfer agent characteristics fundamental to success including degree of budgetary and managerial flexibility of the projects, the commitment and interaction of the collaborating parties, the laboratory researchers' familiarity with the firm's needs. With respect to transfer recipient characteristics, the firm's ability to absorb and apply the results of the collaboration proved to be of great importance.

In their conclusions, Ham and Mowery argue persuasively that quantitative estimates of the direct benefits of these CRADA-based projects is ‘‘unreliable and distorted’’. One of the reasons why Ham and Mowery are less sanguine about direct quantitative estimates of benefits is that most of the benefits accruing are ‘‘indirect and generic’’. Thus, the transfer recipients indicated that ‘‘the CRADA contributed to their overall technical capabilities, rather than benefiting any single product’’ (p. 670) and the chief benefit to the government lab was improved ability to assess the technical needs of potential commercial partners.

From an effectiveness standpoint, the findings of Ham and Mowery about the indirect benefits of CRADAs can be viewed as asserting the importance of the Scientific and Technical Human Capital criterion. These findings echo other studies of cooperative R&D (e.g., Roessner, 1993; Autio and Laamanen, 1995; Feller and Roessner, 1995; Bozeman and Rogers, 1998a,b). (For a contrasting view see Rogers et al. (1998) who found companies to be chiefly interested in obtaining new technology.)

In another recent study (Rogers et al., 1998) of CRADAs, the chief obstacle to effectiveness was the lack of symmetry between the organizational cultures of the federal laboratory and its CRADA partners. Questionaires were mailed (Eto et al., 1995) to the participants in each of Los Alamos National Laboratory's 117 CRADAs in place in 1995, CRADAs valued at US$293 million. They received responses from half the CRADA partners as well as 54% of the federal laboratory personnel active in the CRADAs. Obstacles to the effectiveness of the CRADAs included the length of time taken for CRADAs and the maze of required government bureaucratic procedures. These findings are similar to a study (Gibson et al., 1995) of CRADAs developed at Oak Ridge National Laboratory.

In an earlier study, Berman (1994) examined the impact of CRADAs signed between November 1992 and January 1993. Based on 40 telephone interviews with technology transfer managers at 11 federal laboratories, he found that the major barriers to the effectiveness of CRADAs included industry's lack of familiarity with the technical work at federal laboratories and inadequate federal funding for cooperative R&D. Legal barriers to negotiating CRADAS centered on US manufacturing preference laws, product liability, fair access and intellectual property.

One of the more comprehensive studies of transfer media is the survey of Roessner (1993) of 68 firms which belong to the Industrial Research Institute. In examining firms' interactions with federal laboratories, he considered a wide variety of interactions including contract research, cooperative research, workshops, licensing, sponsored research, technical consultation, employee exchanges, use of lab facilities, lab visits and formal information dissemination through publications. By far the most important category of interaction was contract research, followed by cooperative research. Few valued licensing and more formal interactions.

Another transfer medium that has received a good deal of attention during the past decade is the R&D consortium (e.g., Smilor and Gibson, 1991; Watkins, 1991). CRADAs are in some ways similar to consortia but are generally less institutionalized, involve fewer parties and are more likely to include proprietary agreements. Aldrich et al. (1998) studied R&D consortia in the US and Japan, gathering data from 39 US and 54 Japanese multiform R&D consortia which included, respectively, 1801 US members and 1647 Japanese members. The chief factors associated with degree of information exchange, the authors' focus, were patterns of interorganizational relations and internal diversity of the consortia. However, their model explained results for US consortia much better than for Japanese ones.

Another institutional medium for technology transfer, one that has received somewhat less attention among empirical researchers, is the science park. Felsenstein (1994) provided one of the more important recent studies, comparing 160 high-technology firms in Israel, some located in science parks, some not. The chief finding was that location in a science park seems to provide no direct contribution to innovation but does confer status and prestige and these indirectly promote technology transfer and information flows.

The role of human capital and training in technology transfer is becoming more widely recognized. This medium for technology transfer arises in a variety of ways including, among others, directed training aimed specifically at managing technology transfer (Grosse, 1996), use of consultants (Bessant and Rush, 1995), training of students, especially relocating international students (Nataraajan and Chawla, 1994), personnel exchange or secondment (Hicks, 1993) and, of course, informal relations among bench level scientists (Bozeman et al., 1995).

A general issue pertaining to transfer media, is the influence of intellectual property policies. Consideration of intellectual property law, patents and patent law is beyond the scope of this review. A textbook-length treatment would be required just to consider the most important case law. One recent study is particularly relevant, however, as it pertains directly. Powell and Owen-Smith (1998) examined the role of intellectual property in the life sciences and the transformation of universities. They argue that there is an increasing blurring of the division of labor between industry and academia. One result is increased politicization of government research funding and, particularly, a more intense competition among universities.

6.3. Characteristics of the transfer object

One of the most common distinctions in the literature is between knowledge transfer and technology transfer (Gilbert and Cordeyhayes, 1996). If we classify knowledge transfer as ‘‘scientific knowledge used by scientists to further science’’ and technology transfer as ‘‘scientific knowledge used by scientists and others in new applications’’, then it is the latter that has received most of the attention in the technology transfer literature.

Increasingly, researchers and theorists have shown an interest in the transfer of ‘‘tacit knowledge’’. Grant and Gregory (1997) analyzed case studies of manufacturing technology transfer and the role of tacit knowledge and conclude that the extent of transfer of tacit knowledge often has a major impact on the effectiveness of manufacturing technology transfer. In his study of collaboration among Japanese and British high technology firms, Lam (1997) uses the concept of tacit knowledge in a cultural context, examining its role in mediating friction that occurs as the Japanese ‘‘organizational’’ model of R&D comes into conflict with the British ‘‘professional’’ model.

Among the many categories of transfer object, one enduring focus has been on commercializable products. To what extent do the transfer objects achieve commercialization and what is their rate of commercial success? With respect to federal laboratory–industry interactions, considerable evidence (Roessner, 1993; Roessner and Bean, 1994; Bozeman and Crow, 1990; Bozeman et al., 1995; Geisler and Clements, 1995) indicates that a minority of interactions are motivated by the prospect of directly realized commercial products and that relatively few projects actually result in the company's commercialization of technology transferred to the company. But let us consider results for those companies that do develop and market technological products or processes.

In their study of 219 federal laboratory–industry technical interactions, Bozeman et al. (1995) found that about 22% resulted in a product brought to market. Subsequent studies (Bozeman, 1997; Crow and Bozeman, 1998) using the same found companies marketing products as a result of their federal laboratory interactions were both younger and smaller, substantially so, than the others in the data set. Projects were more likely to lead to a commercialized product if they were initiated by either the companies' R&D managers or by top managers in the company. Projects developed by bench level scientists, lab directors or, in most instances, federal laboratory personnel, were no more (or less) likely to lead to commercial results. Interestingly, but consistent with findings about the importance of indirect benefits (Roessner and Bean, 1994; Ham and Mowery, 1998), the companies commercializing the results of their cooperative projects reported levels of economic benefit lower than other participants. The only set of respondents reporting both low economic benefit and regret at ever becoming involved were the small percentage who set out, as a primary motive, to develop commercial technology and failed.

One way of categorizing transfer objects is in terms of their sector of application, including military vs. civilian. Studies of ‘‘dual-use’’ technology (Watkins, 1990) generally focus on the features of technology (or other transfer objects) for application in both the military and civilian sectors. Cowan and Foray (1995) suggest a strong interaction among sector of use, process vs. product technology and types of learning required for deploying a technology. They hypothesize that knowledge of the life cycles of technologies affects strongly the ‘‘dual-use’’ utility of the technology. Molas-Gallart (1997) provides a typology useful in assessing the appropriateness of technology for dual use. He distinguishes among actors (single unit transfer or two or more units) and modes (adaptation required or not) and concludes that each requires different transfer strategies.

One characteristic of transfer objects that has received some attention is the composition of R&D,

the transfer object's position on the basic research-developed technology scale. Particularly there has been concern about the extent to which basic research is a fruitful transfer object. In a case study of industrial innovation at CERN, Hameri (1996) concludes that well-organized, highly focused interaction with industry is a prerequisite for technology transfer from basic research. Rogers and Bozeman (1997), focusing on 219 federal laboratory–industry partnerships, most involving basic research, found that, compared to all projects, the ones involving basic research had higher costs but also a greater likelihood of yielding a commercial technology project. Findings for a set of case studies yielded quite similar results (Bozeman et al., 1999).

6.4. Characteristics of the demand environment

Market failure has a different meaning in a government policy context, even when government policies are directed at stimulating technology infrastructure and economic development (Feller, 1987, 1997). The usual stereotype of demand for technology is either market-push or market-pull. But often non-market forces shape demand. Dalpe et al. (1992) examined the role of the public sector as the first user of technological innovations. In examining Canadian innovations, they found that 25% of those inventions received their first application in the public sector and concluded that insufficient attention has been given to the public sector's role in shaping demand and markets for technology. Moon and Bretschneider (1997) have focused on innovation demand in the public sector and found that the government broker role is much more effective when government managers take an active role. Bobrowksi and Bretshneider (1994), in a study of a state government technology development agency, found that co-funding is a particularly helpful strategy that a state agency can use to induce demand.

In a study focusing on the flow of scientific knowledge from a university to small and medium enterprises Italy, Azzone and Maccarrone (1997) argue that the changeability of demand, both type and extent, for new technologies requires a ''flexible infrastructure'' rather than a set of fixed, institutionalized resources. Their study of technology transfer in the biomedical industry suggests that the critical mass of demands for technologies and technical competencies is a major factor in determining market impact technology transfer success.

The question of market-''push'' or -''pull'' has clear strategic implications for technology transfer effectiveness (Gander, 1986). Piper and Naghshpour (1996) argue that many public sector technology transfer practitioners tend to assume market-pull and take an ''if we build it they will come'' approach. They argue for a strong market-push approach, adapting contemporary marketing approaches to government efforts to diffuse technology. Focusing on technology transfer from defense laboratories, Spivey et al. (1997) found that defense laboratories tend to employ technology push in transferring technology to civilian use but market-pull when technology is transitioned to defense operations and field agencies.

6.5. Characteristics of the transfer recipient

One of the most important considerations in assessing the effects of the transfer recipient on transfer success is whether the recipient is a government agency, non-profit organization or a business. While most of the technology transfer literature assumes that businesses are the recipient, there is a well-developed literature (e.g., Bozeman et al., 1978; Lambright, 1979; Doctors, 1981) focusing on transfer of technology to government users.

Research comparing directly business and non-profit or government technology recipients consistently finds marked differences in process, barriers to effectiveness and, indeed, definitions of effectiveness. Kingsley and Farmer (1997) and Kingsley et al. (1996) found in their in-depth case studies of 31 state government energy R&D technology development and transfer projects that public regulations often strongly affected technology transfer, generally encouraging it. They also found that when technology partners were sets of government agencies (e.g., energy agencies and transportation agencies) there was a high incidence of successful transfer.

One of the most basic questions about characteristics of the transfer recipient is what type of organization becomes involved as a technology transfer partner. A good deal of information exists on this point. Roessner (1993) found that interest in working with federal laboratories increased as companies' own internal R&D support decreases. In another study, Roessner and Bean (1991; 1994) found that companies with more experience with federal laboratories tended to be larger in terms of budgets and personnel, they were motivated by access to unique technical resources available at the laboratory and they were, in general, more active in acquiring external technical information from a variety of sources, including universities. These findings compliment those of Papadakis (1992) who examined 219 industry–federal laboratory technical partnerships. Another study (Geisler and Clements, 1995) found that companies are generally more interested in the technical expertise, resources and knowledge found in federal laboratories than in discrete products or licenses.

Roessner and Wise (1994) interviewed companies' research directors and chief technical officers about sources of external technical knowledge and found that universities fared considerably better than federal laboratories or other firms, ranking first among companies with R&D budgets in excess of US$500 million. In that same group, federal laboratories were valued less highly than other firms, private databases and R&D consortia. With respect to sources of technical knowledge for new products and production processes, respondents rated in-house R&D as most important, with universities and government agencies being ranked well below such sources as customers, competitors, suppliers and consultants. The results suggest that the cooperative technology policy paradigm has begun to take hold for the largest, R&D intensive companies but less so for small and medium enterprises.

Harmon et al. (1997) set out to determine whether the size of firms involved in university-initiated technology transfer related either to activity or effectiveness. Focusing on 23 different technologies developed at the University of Minnesota from 1983 to 1993, the authors found that business firms involved in transfers could be placed into several groups including, established firms, recently created new ventures or a new company created explicitly to develop and market the transfer object. More than half of the transfers were to large companies that were using the technology to extend existing product lines. In eight cases the recipients were small firms and in three cases recipients were venture capital firms. The remainder were new firms created by the university scientists and inventors seeking to develop and commercialize the transfer object begun at the university; in only four cases did the firms have no prior relationship with the university.

7. Conclusions: technology transfer effectiveness

In this concluding section, the effectiveness criteria of the Contingent Effectiveness Model are used to structure an analysis of the strengths and weaknesses of technology transfer research and theory. Table 5 provides a summary of the effectiveness criteria, key questions, theory base and illustrative studies.

7.1. ''Out-the-door'' criterion for technology transfer effectiveness

The Out-the-Door criterion, if it has any theory basis at all, is rooted in the closed model of bureaucracy — when a bureaucratic superior exercises authority, the bureaucrat obeys or at least gives the semblance of obeying. The assumption of the Out-the-Door criterion is that transfer itself equates with success. According this criterion, the organization participates in technology transfer either reflexively or because there is a directive to do so, but there is not particular regard for the impacts of technology transfer.

Despite the fact that the Out-the-Door criterion entails perfunctory response to external pressures, an understanding of this criterion is vital to any evaluation of university or government laboratory-based technology transfer. In interviews conducted during the past 15 years (e.g., Bozeman and Fellows, 1988; Crow, 1988; Crow and Bozeman, 1987, 1998), the answer to the question ''what motivates your technology transfer activity'' quite often was ''we were told to''. That same response often explained much about increases in CRADA signings.

In short, much public sector technology transfer activity, particularly from the period of the mid-1980s to the early 1990s, was a direct result of formal mandates, not a bottom-up change in the way of doing business. The Stevenson–Wydler Act required establishing technology transfer offices and the setting aside of 0.05% of research budgets for technology transfer. Many laboratories did not quickly comply (US General Accounting Office, 1989), but later

Table 5
Technology transfer effectiveness criteria

Effectiveness criterion	Key question	Theory base	Major advantage and disadvantage
‘‘Out-the-Door’’	Was technology transferred?	Atheoretical or classical organization theory	Advantage: Does not hold transfer agent accountable for factors that may be beyond control. Disadvantage: Encourage cynicism and focus on activity rather than outcome.
Market Impact	Did the transferred technology have an impact on the firm’s sales or profitability?	Microeconomics of the firm	Advantage: Focuses on a key feature of technology transfer. Disadvantage: Ignores important public sector and non-profit transfer; must accommodate market failure issues.
Economic Development	Did technology transfer efforts lead to regional economic development?	Regional science and public finance theory.	Advantage: Appropriate to public sponsorship, focus on results to taxpayer. Disadvantage: Evaluation almost always requires unrealistic assumptions.
Political	Did the technology agent or recipient benefit politically from participation in technology transfer?	Political exchange theory, bureaucratic politics models	Advantage: Realistic. Disadvantage: Does not yield to systematic evaluation.
Opportunity Cost	What was the impact of technology transfer on alternative uses of the resources?	Political economy, cost–benefit analysis, public choice	Advantage: Takes into account foregone opportunities, especially alternative uses for scientific and technical resources. Disadvantage: Difficult to measure, entails dealing with the ‘‘counterfactual’’
Scientific and Technical Human Capital	Did technology transfer activity lead to an increment in capacity to perform and use research?	Social capital theory (sociology, political science), human capital theory (economics)	Advantage: Treats technology transfer and technical activity as an overhead investment. Disadvantage: Not easy to equate inputs and outputs.

studies (e.g., Bozeman et al., 1995) found widespread compliance.

One reason the Out-the-Door criterion is likely to take on even more importance than in the past is the increased concern for quantitative demonstration of results. In the US, the Government Performance and Results Act (GPRA) (US Congress, 1993) has contributed in part to the ''metric mania'' now gripping the US federal bureaucracy. Federal agencies involved in performing or funding science and technology are even more wary than other federal bureaucrats subject to GPRA. They feel their activities, few of which have near term pay-off, are difficult to measure and evaluate. The US General Accounting Office agrees. A recent report (US General Accounting Office, 1997) observed,

> (E)xperts in research measurement have tried for years to develop indicators that would provide a measure of results of R&D. However, the very nature of the innovation process makes measuring the performance of science-related projects difficult. For example, a wide range of factors determine if and when a particular R&D project will result in commercial or other benefits. It can also take many years for a research project to achieve results.

Certainly the notion that the approximately US$70 billion the US federal government spends on R&D (including about US$15 billion at universities) (National Science Board, 1998a, p. A-160) should be subject to systematic planning and evaluation is difficult to contest. Nor is the requirement for the submission of performance indicators to accompany the performance plans an unreasonable one, especially since there is considerable latitude in choice of measures (Cozzens, 1995; Cozzens et al., 1994). But research and technology transfer institutions are in one respect not much different than other organizations — when they are being evaluated they reach for indicators that are easy to find and not easy to interpret negatively. The number of licenses, the number of CRADAs signed and other such straightforward counts meet the joint criteria of ease and innocuousness.

Aside from the need to understand motives in science bureaucracies, there is another respect in which the Out-the-Door criterion is important: it also has the advantage of basing the evaluation criterion on factors largely under the lab's control. Some would say that the lab is at least partly culpable if it transfers technologies to companies who have inadequate capital, manufacturing ability, or market savvy to make a good technology into a good, profitable product. But that is a high standard and requires market forecasting expertise in short supply at the federal laboratories (Piper and Naghshpour, 1996) and universities (Rosenberg and Nelson, 1994; Harmon et al., 1997). The public policy argument of the Out-the-Door criterion is that it is the university or government laboratory's job to create technologies or applied research attractive to industry, but it is industry's job to make them work in the marketplace. In the wake of GPRA and other evaluation initiatives, this argument may no longer fly.

7.2. Market Impact and Economic Development criteria for technology transfer effectiveness

The objectives and the rhetoric of the cooperative technology policy paradigm centers on a Market Impact and its close conceptual cousin, Economic Development. The Market Impact criterion, as the name implies, assesses effectiveness according to the commercial success of the transferred technology or information. The Economic Development criterion is quite similar but written on the broader canvas of regional, and sometimes national, economic growth. Generally, Market Impact pertains to a single firm or just a few firms, but much technology transfer, especially that undertaken by universities and government agencies, is rationalized by broader economic multipliers assumed to flow from technology transfer.

The advantage of these criteria is a richer notion of success. In most instances (public sector technology transfer excepted) there is little appeal to technology transfer that proves commercially and instrumentally barren. An important problem with Market Impact and, especially, Economic Development criteria is misattribution of success and poor understanding failures. If a particular instance of transfer is not commercially successful, is it because the product or process transferred is of limited value, because the transferring agent has not taken the actions necessary to ensure its success, or because of the recipient organization's problems in development, manufacture, marketing, or strategy? Either market-oriented criterion can lead to enormous boundary-setting problems. If a new drill bit project enables deeper drilling, opening up North Sea oil exploration (Link, 1995), how much does one credit the project and prior science? How quickly would the technology have developed if not for the project? Most important, if a US developed technology provides great benefits abroad, what does that do to the accounting?

Despite analytical and evaluation difficulties, Market Impact and Economic Development criteria are in most instances the acid test of technology transfer. The cooperative technology policy paradigm is rationalized in terms of its potential to contribute to competitiveness and, thus, technology transfer with little market result has no place in the paradigm.

During the past decade, many evaluation studies have been produced using either Market Impact or Economic Development criteria, or both. While many of these evaluations have yielded quite positive results, there is an emerging consensus that university and federal laboratory technology transfer have only modest potential for creating new jobs or new businesses. Bozeman et al. (Bozeman, 1994, 1997; Bozeman et al., 1995, 1999; Crow and Bozeman, 1998) and Roessner et al. (Roessner and Bean, 1991; Feller and Roessner, 1995) provide consistent evidence from different data sources that federal laboratory partnerships yield a great deal of value in the transfer of knowledge and, sometimes, physical technologies; they enhance greatly the scientific and technical human capital available to the recipient; they contribute to the recipients' store of ''know-how'', and they put the technology agent more in touch with user needs. There is little direct evidence for federal laboratory–industry partnerships as a wellspring of jobs or new businesses.

Similarly, findings for universities suggest that businesses are created, economic development wealth is generated, but these are not the chief benefits. In their in-depth review of 23 technologies transferred from the University of Minnesota, Harmon et al. (1997) (p. 432) note that ''policymakers should proceed with caution before accepting a notion that new or high technology firms will create significant numbers of new jobs or have substantial immediate economic impact''. This does not imply, however, that such partnerships have little long-range benefit. As Harmon et al. (1997) (p. 432) note:

> (T)he history of science proves that thousands of small, incremental advances are necessary to set the stage for major advances in scientific thinking and discovery — Einstein spoke of standing on the shoulders of giants. It is likely that the commercial and economic benefits provided by the advancement of science appear in a similar pattern. Thousands of small companies, selling products based on modest technological advances, may be necessary to create the conditions conducive to a smaller number of companies expanding into large firms based on more revolutionary technological advances.

A curious finding from the study of Bozeman et al. (1995) of federal laboratory–industry partnerships may reflect just this point. Among the 219 partnerships (mostly cooperative research projects based on CRADAs) the mean average value for company managers' estimates of net economic benefits to the firm was about US$1.5 million, whereas the median estimate was zero. When one takes this finding along with a generally high satisfaction level among participants (92% viewing the partnership as a good investment of time and resources), then it seems likely that direct and tangible benefits are sporadic and not often realized quickly. At the same time, a stream of incremental benefits is realized over a long period of time and, in all likelihood, the partnerships contribute to a complex web of knowledge capital from which firms will ultimately benefit significantly, even if it is not possible to disentangle all the source of knowledge required for innovation and commercial success.

7.3. Political reward criterion for technology transfer effectiveness

During various on-site interviews (e.g., Crow and Bozeman, 1998), university and federal laboratory officials have on many occasions made direct or, more frequently, indirect reference to the political pay-offs expected from technology transfer activities. That is, technology transfer is viewed as a way to enhance political support rather than as a means of creating direct resources or contributing to industrial competitiveness. Thus, it is an instrumental value, a means to an end.

There are at least three possible avenues to political reward. In the least likely of scenarios, the lab is rewarded because the technology it has transferred has considerable national or regional socio-economic impact and the lab's role in developing and transferring the technology is recognized by policy superiors and, in turn, the lab is rewarded with increased funding or other resources. By this view, the Political and the Market Impact criteria are highly complementary. This scenario is not unprecedented but does not commonly occur. In the first place, few technologies have such an impact. But even when there are huge impacts from technology transfer, it is often the case that the laboratory role is not evident to policymakers or the policymakers simply may not provide the expected ''reward''. Budgeting processes usually do not work in such a way as to reinforce such expectations.

Another way in which the Political Reward criterion may yield resource results for the laboratory is through the transfer recipient. Under this scenario, the organization or industry benefiting from the technology transfer, communicates to policymakers the value of its interaction with the university or government laboratory technology transfer partner. The policymaker then, in turn, rewards the lab for being a ''good industrial partner''.

Probably the most common and realistic rationale under the Political Reward criterion is for the lab to be rewarded for the appearance of active and aggressive pursuit of technology transfer and commercial success. In this case, the Political Reward criterion turns out to be much the same as Out-the-Door: activity is its own reward. Much bureaucratic behavior seems to support this view. Often federal laboratories are as active in publicizing their technology transfer and economic development activities as in actually doing the transfer work.

7.4. Opportunity Cost criterion for technology transfer effectiveness

One abiding truth about federal laboratories' technology transfer activity is that it is only one of many technical activities occurring and usually not, at least by the lab scientists' and technicians' view, among the most important. Further, many other activities of federal laboratories are vitally important. Transferring technology takes its place alongside contributing to the advance of basic research and scientific theory, providing equipment and infrastructure for the growth of scientific knowledge, training scientists and engineers, and ensuring the nation can perform its defense, national security, public health and energy missions.

In many cases, the Opportunity Cost criterion represents the views of the bench scientist (Bozeman and Fellows, 1988). The individual scientist or lab administrator may not give a great deal of thought to alternative public policy uses of technology transfer resources, but certainly gives consideration to perceived impacts on the internal R&D budget. [3]

In addition to local project and program concerns about alternative uses of resources, there is another quite significant issue pertaining directly to the Opportunity Cost criterion. Our work on laboratory structure and performance has consistently demonstrated that taking on new missions almost always greatly alters laboratories' output profiles, capabilities, and constituents. With major mission changes the laboratory, perforce, becomes a qualitatively different institution. We (Crow and Bozeman, 1998) refer to this as the ''never neutral principle''. This is not, of course, always bad — only to the extent that the laboratory is already accomplishing an important mission (such as defense technology development or basic research) and that mission will be impaired by significant change and redeployment of resources.

In the case of university technology transfer, the unease about possible effects of technology transfer and, generally, commercial technology activities on the scientific culture and the educational traditions of universities reflects Opportunity Cost thinking. This is the chief focus of the research of Lee (Lee, 1994, 1996, 1998; Lee and Gaertner, 1994).

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[3] During laboratory interviews, we (Crow and Bozeman, 1998) often asked (already knowing the answers) bench scientists how much money was being spent by the lab's technology transfer office or how many people were employed by the office. Their estimates were almost always inflated, often by orders of magnitude.

The Opportunity Cost criterion is important not so much for its direct application in evaluation, but as a conceptual tool encouraging the analyst to take a more global view of universities' or laboratories' activities.

7.5. Scientific and technical human capital criterion for technology transfer effectiveness

Scientific and technical human capital includes not only the formal educational endowments usually encompassed in traditional human capital concepts (e.g., Becker, 1964), but also the skills, know-how, ''tacit knowledge'', and experiential knowledge embodied in individual scientists (Bozeman and Rogers, 1998a,b; Bozeman et al., forthcoming). Many government managers, especially those in the core funding agencies, are as concerned about building up scientific and technical capacity as much as producing discrete impacts from particular projects. Some public managers speak eloquently of their roles in nurturing science. S&T human capital is the sum total of scientific and technical and social knowledge and skills embodied in a particular individual. It is the unique set of resources that the individual brings to his or her work and to collaborative efforts. Since the production of scientific knowledge is by definition social, many of the skills are more social or political than cognitive.

Elsewhere, we (Bozeman and Rogers, 1998a; Bozeman et al., forthcoming) suggest several measures of the scientific and technical human capital embodied in networks (knowledge value collectives) of scientists, technicians and the commercial partners with whom they interact. After conducting extensive case studies of university and government laboratory R&D funded by the Department of Energy's Office of Science (Bozeman et al., 1999), we feel that scientific and technical human capital is an often neglected and invariably underestimated set of criteria for research and technology transfer effectiveness.

In many instances, policy-makers and technology transfer practitioners, especially those in government agencies, take the view that technology transfer, even if it does not have immediate effects from discrete projects, helps build capacity within either a geographic area, a scientific and technical field or an institution (Malecki, 1981a,b; Malecki and Tootle, 1996). Increments to scientific and technical human capital enable future technological and economic development. Rappa and Debackere (1992) and Autio and Laamanen (1995) suggest that evaluation of technology transfer is most appropriately directed to impacts on networks of interconnected scientific and commercial actors. Lynn et al. (1996) and Bidault and Fischer (1994) also provide a strong argument for a network-based concept of effectiveness, in part because their research shows that the specific ongoing relations among networks of technology partners is generally more important than are market factors to transfer effectiveness.

A recent National Academy of Sciences (Committee on Science, Engineering and Public Policy, 1999) analysis of approaches to evaluating federal R&D under the requirements of the GPRA recognizes the importance of the Scientific and Technical Human Capital criterion in evaluating R&D. The report noted (p. 10) that draft strategic plans from science agencies included little or no information about human resources and suggested that ''both research and mission agencies should describe in their strategic and performance plans the goal of developing and maintaining adequate human resources in fields critical to their missions''.

7.6. Technology transfer evaluation and theory: complement or substitute?

Does the evaluation focus of so much of the technology transfer research complement or substitute for research seeking explanatory theories of technology transfer? After reflecting on this review of scores of research studies on technology transfer, the reader has perhaps arrived at an answer to this question. The reviewer's answer is that the evaluation focus both helps and hinders theory. One advantage of most technology transfer evaluations is that they require some sort of empirical base. This is not a small thing. Even today, the technology transfer literature includes a vast number of papers with sub-titles such as ''Conceptual Model for...'' or ''A Typology of...''. In many instances there is no empirical content at all to these studies. Some are valuable and provide keen insights, but it is difficult for explanatory theory to advance purely on the basis of analytical thought experiments. The evaluation orientation gets the researcher away from the office and into the field. However, an evaluation orientation to technology transfer research generally means that the sponsor's interests dictate the choice of research site. This is not always a problem, especially if the sponsor is interested in multiple sites with diverse contexts. But choosing research subjects and sites on the basis of sponsor interests rather than according to theoretical dictates often results in incomplete pictures of technology transfer. In many instances, the evaluation sponsor is interested in a single case. Obviously, this impedes the generalizability of technology transfer research.

An advantage of the evaluation orientation is that it stimulates healthy controversy. Studies that sometimes inform public policy debates (as many of the studies cited here do) are apt to be subjected to public scrutiny and to engender criticisms well beyond the circle of highly specialized researchers who happen to be interested in a topic. A researcher who expects to defend findings is generally a particularly careful researcher and one who strives for strongly supported explanation. But the high visibility and political stakes in evaluation studies of technology transfer can be a disadvantage. The researcher must constantly be vigilant in guarding against politicization and even distortion of results.

In short, the evaluation dominance in university and government laboratory technology transfer research is a mixed blessing. Because there is interest in evaluating technology transfer, research is supported by mission agencies and there is much more technology transfer research (and, I think, much greater understanding) than there would otherwise be. Likewise, evaluation objectives serve as a reality check. But if the ‘‘dependent variable’’ is almost always some concept of near-term effectiveness, it is easy to lose sight of important aspects of technology transfer. There are several hundred publications on technology transfer, but many topics are neglected. We still know almost nothing about technology transfer politics, including distributional outcomes of technology-based economic development. We have little understanding of many critical impacts, such as developments in scientific and technical human capital, occurring over long time periods. We know little about the impact of technology transfer activities on institutions, their designs and their full range of capabilities. Public policies of the 1980s and 1990s unleashed the cooperative technology policy genie from the bottle and research shows that some wishes have been granted. But genies, not just wishes, bear watching.

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