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Paradigm-Changing vs. Paradigm-Deepening Innovation: How Firm Scope Influences Firm Technological Response to Shocks

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We examine the direction of firms' research efforts as they respond to the shock of a sharp increase in the price of a key input. In terms of direction, firms can respond to this shock with *paradigm-changing* investments that develop technologies to use substitute inputs or with *paradigm-deepening* investments that develop technologies to improve the utilization efficiency of the existing input. We develop a framework that suggests that firms' emphasis on paradigm-changing versus paradigm-deepening investments depends on the degree of input-relatedness across their businesses. We test our hypotheses by examining the responses of large manufacturing firms in the United States to the oil shock of the early 1980s. Our framework predicts and our results show that the more related a firm's businesses are, the larger its investments into paradigm-changing technologies are and the smaller its investments into paradigm-deepening technologies in response to the oil shock are. We identify the implications of these findings for technological evolution and diversification literatures.

Keywords: technological change; innovation; evolutionary approaches; shocks
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Introduction

In this paper we examine how large established firms react technologically to a substantial increase in the price of a key economic good such as oil. The increase in price of such a ubiquitous good serves as a broad-based shock that can significantly influence a firm's profits. Research suggests that firms may respond to such shocks by directing their technological efforts toward reducing dependence on the expensive good (Ruttan 1997) (a) by improving the efficiency of the current technologies that continue to rely on the good so they use less of it or (b) by seeking substitutes for the expensive good. In this paper, we examine how a firm's diversification moderates its technological response along each of the above directions.

A firm's diversification has long been argued to be a significant influence on its technological investment patterns (Nelson 1959). The core arguments in this context have focused on (a) how the broad scope of a firm provides incentives to invest in research and development (R&D) by making it easier to exploit the spillovers from R&D—for instance, in businesses different from those originally envisaged—and (b) how a firm's scope may help the recombination process central to innovation (Alonso-Borrego and Forcadell 2010, Baldwin and Scott 1987, Cohen and Levin 1989). Yet prior work connecting a firm's diversification with its technological investments primarily focuses on the quantum of those investments. We build on these ideas by examining the relationship between diversification and the *direction* of a firm's research efforts. Furthermore, although prior work has focused on the implications of product-market diversification for technological outcomes, we focus on the implications of factor-market diversification or input-relatedness for technological outcomes.

We examine the diversification-technological efforts link in the context of firm responses to an exogenous and significant shock, a contingency not previously examined in the literature. When the price of a key input rises, it can significantly impact the bottom line of a firm, especially if the firm is heavily dependent on the input for production. The more dependent is a firm on the input, the more acutely it feels the shock and the more pressured it is to respond. Mounting a response to such a shock, however, requires an ability to coordinate action, both within the firm and potentially beyond it. Diversification represents a differentiation of economic activity within the firm and differentiation of activities has direct implications for coordinated action in organizations (Kretschmer and Puranam 2008, Lawrence and Lorsch 1967). Conceptually speaking, it would then appear that a firm's diversification may significantly condition its response to a shock. However, the mechanisms through which this influence may occur remain to be articulated, a task that we take up here.

Understanding the technological response of large diversified firms to shocks is also important because it provides a window into the process of technological evolution (Dosi 1988, Gilsing and Nooteboom 2006, Tegarden et al. 1999). Research suggests that technology usually evolves within the constraints set by prevailing technological paradigms (Dosi 1988); some firms may respond to the shock by continuing along the path of the incumbent paradigm and work within its ambit (Cyert and March 1963, Popp 2002). However, a shock can also provide an important stimulus for firms to invest in new technologies that disrupt the existing equilibrium and thereby sow the seeds of a new technological paradigm. This possibility draws attention to the distinction between paradigm-changing and paradigm-deepening technical change. We introduce this distinction and examine some of its antecedents.

Theory and Hypotheses

To better understand the process of technological evolution, we combine ideas from two prominent perspectives on technological change: (1) the induced innovation perspective (Popp 2002, Ruttan 1997) and (2) the technological paradigms perspective (Dosi 1988). These two perspectives have largely developed independently and emphasize different aspects of technological evolution.

The induced innovation perspective argues that a significant increase in factor input prices spurs innovative efforts to reduce the consumption of the focal input (Hicks 1932, Popp 2002, Ruttan 1997). These dependence-reducing efforts can be exerted along two directions: (1) factor-saving innovations that focus on using the input more efficiently (e.g., inventing processes or products that use less oil) and (2) factor-substituting innovations that focus on replacing the input with another (e.g., inventing a process or product that runs on solar energy rather than oil). However, this perspective does not distinguish between these two directions in categorical terms because it implicitly assumes frictionless substitution between different combinations of inputs: firms that are using one combination of inputs switch almost instantaneously to another optimal combination in response to a change in factor prices. Yet this abstraction assumes away a fundamental feature of technical change: that technical change does not seamlessly and continuously evolve in any direction of a strategist's choosing. It assumes instead that change evolves in a path-dependent fashion along certain paths and not others (Dosi 1988).

The qualitative distinctions between the two directions of technological investments and the full import of choosing one direction over the other can be better understood by borrowing ideas from the technological paradigms perspective (Dosi 1988) that stresses the linkages between innovations and the surrounding technoeconomic system. The technological paradigms perspective integrates three influences on the rate and direction of technical change: demand pull (Schmookler 1966), which is the influence of users' needs and preferences; supply push (Jaffe 1986, Rosenberg 1975), the influence of available scientific and technological knowledge; and appropriability conditions (Schumpeter 1942, Teece 1986), the influence of the institutional environment that allows inventors to appropriate value from their inventions. The core idea in this perspective is that technological growth occurs within the boundaries of a paradigm, with successive innovations forming "a pattern of solutions" along a trajectory defined by the existing technoeconomic consensus (Dosi 1988, Helfat 1994, Sahal 1985).

When the input in question is as ubiquitous and as enmeshed in the surrounding technoeconomic system as oil, substituting the input is qualitatively different from improving its usage efficiency. To effectively substitute such inputs, not only does a firm need to develop substitute technologies but it also needs to change and develop several corresponding relationships in the external environment: regulators and customers need to be convinced about the safety and efficacy of using an unfamiliar and untested technology, new supplier relationships need to be forged, and new complementary investments need to be fostered in the environment (e.g., developing infrastructure for battery charging stations). Thus, substituting such inputs is akin to developing a new technological paradigm, whereas innovating to increase the efficient usage of these inputs helps perpetuate the existing paradigm. Given the magnitude, range, and type of efforts involved in factor substitution of a key input, and building on the literature on technological paradigms, we believe that a more accurate characterization of such innovative efforts is to describe them as *paradigm-changing* innovations. Likewise, factor-saving innovations may be described as *paradigm-deepening* innovations.

We argue that by clubbing both these types of innovations together and failing to consider firm heterogeneity, the induced innovation perspective ignores an important possibility—that the marginal attractiveness of the two types of innovation investments may differ for firms depending on their prior commitments—in this case their existing diversification pattern. To analyze this possibility, we need to understand the distinctions between these two types of innovations in greater detail on one hand and the impact of a firm's diversification on its technological investment decision criteria on the other.

Paradigm-Deepening vs. Paradigm-Changing Innovations

According to Dosi (1988, p. 1127), a technological paradigm can be defined as a "'pattern' of solution[s] of selected technoeconomic problems based on highly selected principles derived from the natural sciences, jointly with specific rules aimed to acquire new knowledge and safeguard it, whenever possible, against rapid diffusion to the competitors." The concept of a technology trajectory highlights that technical progress often occurs along clearly defined paths, or "innovation avenues," addressing commonly perceived economic and technological trade-offs defined by a paradigm (Dosi 1988, Sahal 1985). Thus, a technological paradigm includes several distinct components: (a) a shared understanding of user needs and technoeconomic problems embodying those needs, (b) a set of product or process attributes flowing from these needs that serve as "technological guideposts" (Sahal 1981, 1985) to focus research efforts into certain specific directions (Rosenberg 1975), (c) commonly held beliefs about the most effective paths to improve these attributes that legitimize certain behaviors and discourage others (Dosi 1988, Kuhn 1970, Nightingale 2008), (d) a set of scientific principles that can be brought to bear on these problems, (e) a reasonably well-defined set of material technologies to create the products and processes that embody the paradigm (Dosi 1988), and (f) relative clarity about the prospects and mechanisms of appropriating value from any innovations so created. A technological paradigm is thus simultaneously a technological, cognitive, economic, and behavioral phenomenon.

Investing in a new technological paradigm is qualitatively different from making investments consistent in the existing paradigm. Three differences are especially relevant for our analyses. First, paradigm-changing research is more uncertain and less likely to yield results in the short term. Second, paradigm-changing research is more exploratory and basic. Third, to be economically successful, paradigm-changing innovations require the coordination of many concurrent changes in the external technoeconomic environment. We examine these considerations in detail below.

Once established, a paradigm reduces uncertainty—it focuses attention on particular kinds of problems to be solved using particular types of approaches, with particular expectations about the returns from such efforts. In contrast, the preparadigmatic stage is characterized by uncertainty not only about the technological and commercial success of an idea but also about fundamental questions such as what problems to solve, how to approach those problems, and what to expect from the solutions (Schilling 1998). Thus, making commitments to a new technological paradigm entails facing uncertainty an order of magnitude greater than continued investment in an established paradigm.

The uncertainty of preparadigmatic research is further heightened by its nature; it involves exploring new scientific bases and learning about and applying principles that are distant from current knowledge bases. Such distant, early-stage search is more basic and less applied and most likely to occur through centralized corporate research laboratories than in business unit research facilities that focus on more applied, narrowly defined projects (Argyres and Silverman 2004, Nelson 1959). Furthermore, the end uses of such basic research are unpredictable; it may yield results that spill over to or that are more useful for purposes distant from intended goals (Nelson 1959). Thus, divisions that are ultimately interested in what their investments yield for *their* business are less likely to favor such technologies (Argyres 1996, Argyres and Silverman 2004). In addition, technical research at business unit level usually pertains to the specific needs of the unit and is driven by the unit's immediate day-to-day requirements (Argyres and Silverman 2004, Christensen 1998, Pitts 1977). Paradigm-changing innovations are therefore more likely to require central research resources. In contrast, paradigm-deepening innovations are more likely to be explored and implemented at the divisional level because they seek to enhance the efficiency of existing technologies that are more likely to be specific to a division.

Apart from technological uncertainties, firms also need to resolve many commercial uncertainties to make an emerging paradigm successful, especially if it involves substituting a critical and ubiquitous input. A fundamental input such as oil is often embedded in an economy within a maze of interconnected relationships. To replace such an input requires action on many fronts; a multitude of interorganizational and institutional complements need to be developed, each with its own set of hurdles. For instance, to switch from one set of technologies (say, oil-based) to another (say, solar-based), firms must identify new sets of effective and reliable suppliers and forge relationships with them or convince their existing suppliers to concomitantly invest in new assets to support the new technology. They may have to confront user concerns about the new technologies and garner support from the complementors of the new technology. Finally, they may need to convince and educate many regulatory bodies about the attributes of the new technology—it is safe, it is really less toxic for the environment, etc. Further, this effort must occur in light of both confusion born out of technoeconomic uncertainty (will the performance of the scaled-up solar engine match up to predictions?) as well as the uncertainty created by strategic behavior of opponents of the new technology. Dosi (1988, p. 1128) noted that a technology paradigm represents a "technology of technical change." Our analysis suggests that supplanting an existing paradigm requires not just a new technology of technical change but also a new *commerce of technical change*.

In short, the above discussion shows that compared with a paradigm-deepening response, a paradigm-changing response is likely to entail more basic research with uncertain, longer payoff results and be less amenable to clear financial projections. Such research is more likely to be conducted with centralized R&D resources (Argyres and Silverman 2004, Kay 1988) and thus requires at least a broad consensus across corporate management and at least some of the businesses. Furthermore, to be economically successful, paradigm-changing innovations require the coordination of many concurrent changes in the external technoeconomic environment. An individual firm's likelihood of achieving these external changes is likely to drive its decision to pursue such innovations.

Type of Diversification and Choice of Technological Response

For a firm, the relative attractiveness of the two types of technological responses depends crucially on which response is better aligned with its organizational systems and decision criteria, which in turn are significantly affected by how related its businesses are (Hoskisson and Hitt 1988). The relatedness of a firm's businesses influences its ability to mobilize central resources (Christensen 1998, Hill et al. 1992, Pitts 1977, Vancil 1979), how deeply its corporate managers understand its constituent businesses (Hill and Hoskisson 1987, Vancil 1979), its leverage over the external environment, its degree of reliance on financial logic in decision making, and the risk preferences of its middle managers (Hoskisson et al. 1993). These factors correspond directly to the determinants of a firm's choice between investing in paradigm-deepening and paradigm-changing innovations and therefore influence which response a firm chooses.

Although a firm's businesses can be related along many dimensions, of particular relevance here is the similarity of resources used by its different businesses. This resource similarity, or *input-relatedness*, forms a key basis for realizing economies of scope (Wernerfelt 1984). To exploit these similarities, firms have to develop and institute reward systems and organizing mechanisms that facilitate cooperation and coordination (Hill et al. 1992, Zhou 2011). For instance, to achieve economies of scale and scope in procuring supplies from factor markets, firms with related businesses share supply chains between their divisions and avoid internal conflicts (Zhou 2011); reward systems that encourage cooperation among division managers are key to this strategy (Hill et al. 1992).

The more related a firm's businesses are, the more economically beneficial is the strategy of sharing resources. Sharing resources across businesses, however, implies creating and managing interdependencies. Classic organizational tools to manage such interdependencies are the centralization of the management of shared resources and grouping of the interdependencies under a central authority (Thompson 1967). Firms with related businesses are therefore more likely to depend on centralized facilities, resources, and operating functions such as R&D for their activities (Christensen 1998, Vancil 1979). The empirical evidence is also consistent with these arguments. Hill et al. (1992) found that centralizing and promoting internal cooperation is beneficial to related diversifiers. Vancil (1979) found that the use of centralized operations such as R&D and sales is positively correlated with the relatedness of a firm's businesses.

The relatedness of a diversified firm's businesses also impacts how deeply its corporate managers understand its different businesses. The more dissimilar the resources needed for the success of a firm's various businesses are, the greater the strategic variety the corporate managers of the firm face. Greater strategic variety reduces how deeply a firm's corporate managers understand the challenges and constraints facing the individual businesses (Hill and Hoskisson 1987). The shallower this understanding is, the less likely managers are to choose strategic responses based on strategic imperatives and ambiguous judgmental criteria and the more likely they are to make choices based on financial logic and justifications (Thompson 1967). Furthermore, as the variety in challenges facing a firm's different businesses increases, comparing proposals across businesses becomes more difficult (Dundas and Richardson 1982, Williamson 1985). In such circumstances, financial calculations provide an easy way to allocate resources (Ackerman 1970, Bower 1970, Hill and Hoskisson 1987, Lorsch and Allen 1973). Thus, corporate managers of firms with more dissimilar businesses are more likely to prefer a strategic response based on clear financial projections of its payoffs rather than one based on qualitative assessments of more ambiguous strategic criteria.

These differences in the mode of decision making also lead to differences in the risk preferences of managers. The prevalence of financial logic in decision making and the importance of unambiguous performance criteria such as the return on investments encourage division heads to take a short-term view and eschew risky long-term decisions (Hoskisson and Hitt 1988). These effects can be reduced through the use of centralized research projects wherein R&D managers can be placed in a single cost center and receive lower-powered incentives to engage in more uncertain research (Argyres and Silverman 2004). However, the feasibility of such a solution increases with relatedness between businesses. With completely unrelated businesses it may be difficult to derive consensus on what projects such a central unit should undertake. Relatedly, central research projects are most beneficial when they correct the underinvestment by the business units in spillover-heavy research projects (Argyres and Silverman 2004). Such projects are more likely to be found when the businesses are similar to each other.

Related diversification also increases a firm's ability to institute changes in the surrounding ecosystem. Since a related diversifier provides products to a wide variety of niches within a broad business area, it can claim to champion the cause of the "industry" to institutional constituents. Presence in a broad array of subsectors gives it legitimacy to argue for the industry's cause. Such a broad presence within the industry also enables a firm to have relationships with a broad set of extra-industry partners. For example, compare two firms within the transportation sector, one that operates only in the automobile business and the other that operates in automobiles, motorcycles, and other transportation subsectors. The latter will have relationships with a broader array of participants, such as suppliers, regulators, etc., and therefore will be better able to push for institutional changes in the sector.

The organizational context associated with increased relatedness of businesses—the centralization of resources (Christensen 1998, Pitts 1977, Vancil 1979), the reduced need of financial logic in decision making (Hoskisson et al. 1993), and the leverage over the firm's external environment—is well aligned with the attributes of paradigm-changing technological innovations. Paradigm-changing technological research is characterized by high risk and long gestation periods and thus needs greater employment of central resources, such as basic R&D. Centralization and the milieu of cooperation in related diversifiers are more suitable for mobilizing such central resources. Furthermore, given the technological and commercial uncertainties of paradigm-changing innovations, tight financial projections may not be available, so investing in such innovations may require a more subjective mode of decision making. Reliance on such subjective decision making is more likely as the relatedness between a firm's businesses increases. To be successfully deployed, paradigm-changing innovations also need the firm to negotiate a number of changes in the external environment; the related diversifier's greater leverage over the environment through its extra-industry partners makes paradigm-changing innovations more attractive to it.

Some of these arguments implicitly assume that the market for technology is imperfect. Otherwise, firms would be willing to invest in technologies with high spillovers regardless of the relatedness of their businesses and consequent ability to capture the spillovers internally since they could simply out-license the results to obtain the same economic return (see Teece 1982, 1986). Yet theory and evidence from technology markets suggests that for most firms out-licensing is not a natural or primary goal for funding R&D projects (Arora and Gambardella 2010, Lichtenthaler and Ernst 2007). For most manufacturing organizations of the type covered in our sample, research projects are likely to be argued and approved on the basis of direct payoffs in the form of product or process improvements, with limited consideration provided for the possibilities of out-licensing.

Arora and Gambardella (2010, p. 775) provided substantial evidence that in the 20th century, "the producers of innovation were also largely their own users," especially large firms. Large firms (i.e., firms of more than 250 employees) offered only a small percentage (16%) of their patents for licensing and actually out-licensed an even smaller percentage (9%). They also cited evidence (Lichtenthaler and Ernst 2007) to show that large firms "do not typically have structured managerial processes for licensing their technologies, and do not focus on licensing through dedicated personnel, organization units or resources" (Arora and Gambadella 2010, p. 784). Thus, evidence suggests that for most large firms, out-licensing is not a typical or common cause for investing in a technology. Indeed, studies of the markets for technology conclude that the extent of such markets is much lower than it could be if market imperfections were removed (Arora and Gambardella 2010). However, as things stand, transaction costs in knowledge exchange, fear of competitive implications of out-licensing technology, and underdeveloped organizational structures and routines for this task all suggest that our implicit assumption that firms will not invest in paradigm-changing technologies on the expectation that they can out-license the knowledge is reasonable.

It is possible that greater relatedness among a firm's businesses increases the difficulty of changing its processes to use a substitute input because of the interdependence between its businesses. A competing argument, however, suggests that firms with related businesses may nevertheless be more motivated to invest in paradigm-changing technologies because these firms are more at risk from the shock of high input prices. The shock affects several of their businesses simultaneously and may represent a serious, even existential, risk, motivating action in spite of the complexities involved. Although conducting broad-based change in an organization is difficult, research suggests that an adverse shock can provide the impetus for such changes (Zajac and Kraatz 1993). Also, because we study technological innovations rather than actual organizational changes, it is quite possible that firms with related businesses invest in these technologies to create an option for a subsequent organizational transformation. Whether they actually engage in the undoubtedly risky organizational transformation subsequently is beyond the scope of the current study. Diversification into unrelated businesses, in contrast, reduces a firm's need to react to the oil shock: technically, the greater extent of unrelated diversification has "already solved" the problem of a shock in any of its individual businesses. Based on the preceding arguments we predict the following.

HYPOTHESIS 1 (H1). *A firm's related diversification positively moderates its investments into paradigm-changing technologies in response to oil shock*; *the more related a firm's businesses are, the larger its investments into paradigm-changing technologies are in response to the oil shock.*

In contrast to the technologies that seek substitutes for the key factor, technologies that focus on utilizing the factor more intensively or efficiently deepen the existing technological paradigm. As discussed earlier, such technologies are likely to have three key characteristics: they require less central resources, they provide a clearer and quicker path to payoffs, and they entail relatively quantifiable returns. These characteristics make these technologies increasingly attractive investments to firms the less related their businesses are. Such investments promise relatively clear and timely financial returns (consistent with the incentives of such firms), and their significantly lower fixed costs allow them to be executable at the individual divisional level without requiring extensive coordination (consistent with the organizational context of such firms).

Of course, lower fixed costs and the promise of immediate results should also be attractive to firms with businesses that are more related to each other. However, two arguments suggest that at the margin, greater relatedness between a firm's businesses weakens its commitment to paradigm-deepening innovations. First, it is likely that for any firm, the total resources that can be committed to input-saving inventions are limited relative to the overall research budget, which also has to fund product and process improvements along many other dimensions (e.g., more convenience, comfort, safety). Furthermore, paradigm-deepening and paradigm-changing inventions are likely to reflect fundamentally different projects and commitments and represent different technological trajectories. Committing resources to one trajectory will facilitate further progress along that trajectory (Dosi 1988), but not along the other trajectory. Hence, investments in paradigm-deepening technologies are likely to be in competition with paradigm-changing ones at least to some degree. As a firm's businesses are increasingly related to each other, this competition is likely to become more intense as both types of investments become attractive but only a few projects can be funded. In contrast, when a firm's businesses are increasingly unrelated to each other, paradigm-changing investments become less attractive and permit less the favoring of paradigm-deepening technologies. Thus, other things being equal, increasing levels of unrelatedness in a firm's businesses should favor paradigm-deepening investments.

A second argument also suggests the above conclusion. Investments into paradigm-deepening technologies address a highly salient problem—an observed shock whose solution is marketable in both internal (within the division and corporation) and external audiences (as lowering oil consumption is socially desirable). Given that the incentives to conduct paradigm-changing research are weak as unrelatedness increases, engaging in paradigm-deepening research also provides a legitimacy benefit—the corporation is perceived as doing something about the problem (and in the specific case of oil, it is perceived as being responsive and responsible). The need to obtain legitimacy through paradigm-deepening investments is lowered as the relatedness of businesses grows, as such firms are likely to be engaging in paradigm-changing investments (and hence tackling the input problem) anyway. Based on these arguments, we predict the following.

HYPOTHESIS 2 (H2). *A firm's related diversification negatively moderates its investments into paradigm-deepening technologies in response to oil shock*; *the more related a firm's businesses are, the smaller its investments into paradigm-deepening technologies are in response to the oil shock.*

Methods and Measures

The oil shock of the 1970s and the early 1980s was triggered by ferment in major oil producing countries of the Middle East. Between the end of World War II and the early 1970s, the price of oil was stable at about $20 (prices in this paragraph are in 2009 dollars) per barrel. However, during the first oil shock in the mid-1970s, the price jumped to around $40–$50 per barrel and then dramatically to more than $100 per barrel in 1981. From 1981, the price of oil started falling from that peak but still remained significantly higher than the prices of the last decade till 1986.

This price rise was significant enough to make managers respond. A key input's price that remained about 2.5 times its long-term postwar average for almost a decade invited considerable corporate action (Newell et al. 1999, Park and Labys 1994). As a result, energy intensity in the U.S. manufacturing sector declined by 25% between 1980 and 1985 (Park and Labys 1994). Furthermore, this response was driven by both superior efficiency in the use of oil as well as the use of alternative technologies (Popp 2002). Although previous research demonstrates the technological response of the U.S. industry as a whole to the oil shock (Popp 2002), how and why individual firms differed in their response is still not completely understood. These factors make the oil crisis a unique setting to study the technological responses of firms to an external shock.

Data and Sample

We create a longitudinal set of large diversified firms by combining data from five major data sources: the TRINET database, the Compustat database, the U.S. Census Bureau's Census of Manufacturers file, the U.S. Bureau of Economic Analysis's Input-Output Structure of the U.S. Economy data set, and the NBER patent data obtained from Bronwyn Hall's website (Hall et al. 2001).[1] We use *Fortune*'s list of large American firms from 1981 to identify the 250 largest corporations in the United States. From this broad sample, we identify the major firms in the U.S. manufacturing sector (whose main business is listed in a Standard Industrial Classification (SIC) code between 2011 and 3999) and drop service firms because our arguments on innovation are tested through patenting behavior, which is difficult to measure for service firms. We match this sample with the TRINET and Compustat data sets to yield a sample of 106 firms for which data are available on all three data sets and are all from manufacturing firms. We use the TRINET data from 1981 to 1985 to get information on the sales of a firm in each of its businesses at the four-digit SIC level. TRINET data are available for only the odd years, and the 1981–1985 period is closest to the oil shock. By 1987, the oil prices had stabilized at pre-oil-shock levels or below. Unfortunately, TRINET data are not available for the period before 1980.

We use the U.S. Bureau of Economic Analysis's Input-Output Structure of the U.S. Economy data to construct a continuous measure of the overall oil dependence of a firm. The input-output (IO) tables give us information on how much oil is used for a dollar value of output in a given industry for every year ending in 2 or 7. These data, along with TRINET data, allow us to construct a firm's overall dependence on oil. We use the values from 1982 IO tables because they are closest to the time period of our study. To account for the fluctuations in oil prices, we weigh the oil-dependence values with the oil prices prevailing that year (oil prices obtained from http://www.forbes.com/static_html/oil/2004/oil.shtml, accessed August 2006). We also use the data from the IO tables and TRINET data to construct our measures of relatedness. We use Compustat for time-series financial data. We use the Census Bureau's Census of Manufacturers and Annual Survey of Manufacturing files to construct the measures of the economic environment facing the firms. We then match the firms to the NBER patent database to identify the patents obtained by these firms.

Model

We test our hypotheses by examining how the relatedness of the businesses in a firm's portfolio impacts its technological response to the oil shock. To test our two hypotheses, we examine the oil shock's impact on two dependent variables, *nParadigm-ChangingPat* and *nParadigm-DeepeningPat*. The former, paradigm-changing technology patents, represents a firm's research efforts into technologies seeking alternative new inputs as sources of energy. The latter, paradigm-deepening technology patents, represents a firm's research efforts into technologies that reduce the demand for energy; these inventions do not seek alternative sources of energy but rather make the products and processes more energy efficient (Popp 2002).

It is, of course, possible for firms to respond to such a shock through embodied innovation, i.e., by purchasing new capital equipment (e.g., more energy-efficient machinery invented elsewhere). However, understanding the determinants of such embodied investments represents a different question, which would demand different data and theory. For reasons of theoretical focus (and lack of data availability), we restrict our attention to the output of the firm's own R&D efforts rather than examine their purchases of innovation developed elsewhere. Understanding the determinants of firms' internal R&D investments is important in its own right because internal R&D can be a source of competitive advantage and superior adaptation to a shock for manufacturing firms (such as we study) in a way that purchases of embodied innovation from a common set of suppliers are unlikely to be.

That said, we note that a firm's purchases of embodied innovation from other sectors of the economy could impinge on its own willingness to conduct R&D to solve the problems created by the oil shock and thus affect its investments into paradigm-changing and paradigm-deepening research. Unfortunately, there is no easy way to obtain information on firms' purchases of such oil-saving equipment, and this will remain a limitation of the current paper.[2] We did, however, try to speculate on what the effects of such embodied innovation purchases might be, and we note that such embodied innovation is more likely to "crowd out" paradigm-deepening responses than paradigm-changing responses. This is because (a) choosing between different technological solutions without in-house technical know-how is far more difficult in the earliest periods of a new paradigm since the parameters of evaluation are not well established, and (b) in a preparadigmatic stage, evaluating which external partner is likely to be reliable and survive is more difficult. Note that we study the period just after the oil shock, so no new paradigm has been established; i.e., we are studying an early stage in the new paradigms.

Note also that the strategy of adopting embodied innovations is relatively more amenable to financial projections, an attribute more important for the decision process of unrelated diversifiers. These observations together imply that ours is a conservative test. Since embodied innovations are more likely to reduce paradigm-deepening innovations for unrelated diversifiers, and we predict that unrelated diversifiers are more likely to invest in paradigm-deepening innovations, the presence of embodied innovations makes it more difficult for us to find results supporting our hypothesis.

Since our dependent variables are count variables, a Poisson or negative binomial specification is appropriate for our tests. The likelihood ratio test for the overdispersion parameter yielded a chi-squared value of 16.74 in paradigm-deepening and 29.41 for paradigm-changing regressions with one degree of freedom, indicating significant overdispersion. Consequently, we employ negative binomial specifications. Because the data for the major independent variables are available only for the odd years, we lag the independent variables by two years. We calculate some of the missing values for control variables by interpolation. Nevertheless, some observations drop out of the final regressions, as one or more of the variables remain missing.

Firms differ in their inherent technological capabilities and in their propensity to search in a particular direction. Given the path dependency of technological search, the unobserved firm-specific propensity to search in certain types of technologies, rather than the oil shock, may drive the observed pattern of technological investments. We follow the technique recommended by Blundell et al. (1995) of including fixed effects through "presample"-dependent variables to control for such unobserved heterogeneity: the dependent variable in the presample period (i.e., in the period before the one used for sampling) is used as an instrument for the unobserved heterogeneity between firms. We compute the corresponding variable for each of the dependent variables, *nParadigm-ChangingPat* and *nParadigm-DeepeningPat*, for each firm for the presample period from 1976 to 1980 and use it as a control in our specifications.

Our theory explores how a firm's technology strategy (Y) responds to the oil shock ($X1$) as a function of its diversification ($X2$). To test this relationship, we use the variations in the extent to which firms were affected by the oil shock, i.e., the level of oil dependence, to identify the effects of the shock using just the postshock period. Since these firms are active in multiple, different businesses, and the incidence of the oil shock on these businesses is not equal, then, clearly, some firms are more significantly affected by the shock than others. Thus, the cross-sectional variance in the extent to which firms were affected by the shock (variations in their levels of oil dependence) can be used to proxy the shock. Then the measure of oil dependence is interacted with the level of related diversification to identify the moderating effect of relatedness of a firm's portfolio of businesses.

Measures

Dependent Variables. We test our hypotheses by measuring a firm's research efforts into oil-substituting technologies that entail a new paradigm and into efficiency-enhancing technologies within the existing paradigm. While studying the economy-wide response to oil shocks, Popp (2002, 2006) identified the key technological subclasses in the U.S. Patent Classification System pertaining to technologies that reduce dependence on energy. He further divided the subclasses into ones that indicate a search for new sources of energy (and increase energy supply) and those that pertain to increasing the efficiency of production processes or products so that they use less energy (decrease energy demand).[3] We use his classification for our measures. The research pertaining to alternative sources for energy represents efforts toward paradigm-changing technologies. The research done to improve the energy efficiency of current processes and products represents efforts toward paradigm-deepening technologies. For each firm-year in our sample, we calculate two count variables:

(a) $nParadigm\text{-}ChangingPat_{i,t}$: the number of patents applied by firm i in year t in technological subclasses identified by Popp (2002, 2006) as involving alternative sources of energy, and

(b) $nParadigm\text{-}DeepeningPat_{i,t}$: the number of patents applied by firm i in year t in technological subclasses identified by Popp (2002, 2006) as reducing demand for energy.

Independent Variables. We use measures of oil dependence and input-relatedness as our independent variables.

Total oil dependence of the firm. To construct a firm's overall dependence on oil as an input, we match the TRINET database with the IO table of the U.S. Bureau of Economic Analysis. Using the IO tables, we obtain the information regarding how much oil is used (both directly and indirectly) in producing one dollar's worth of output for each industry at the SIC level. We multiply this with the oil prices prevailing in that year to get a measure of how important the increase in oil prices is for firms in a particular industry. This is the industry-specific oil-dependence measure for an industry i; let us call it $IndustryOilDep_i$.

To calculate a firm's overall oil dependence, we supplement the data from the IO table with the TRINET data and compute for each firm k and industry i the percentage of sales of i. We then calculate the weighted sum of the industry-specific oil dependence of each four-digit industry the firm has operations in using the percentage of sales as weights. Thus, the measure of overall oil dependence of a firm k in year t, $Total\ oil\ dependence_{k,t}$, is calculated as follows:

$$Total\ oil\ dependence_{k,t} = \sum_i (S_{ki} \times IndustryOilDep_i).$$

Here, S_{ki} is the proportion of sales of industry i in firm k.

Input-relatedness of a firm's businesses. Our theory connects the relatedness of a firm's businesses with its technological response to the oil shock. We conceptualize businesses to be related when they share similar inputs and production processes. This conceptualization is appropriate, given our focus and theory. Our focus is on an input shock, and it is very likely that any input is used in complementarity with other inputs. As firms modify their processes to become more efficient in their use of oil, it is likely that businesses that share the same input profiles may be motivated to cooperate in achieving such goals. Furthermore, similarity in input profiles is likely to relate quite strongly to similarity in supplier networks, similarity in dependency on external constituents, and the likelihood of organizations developing coordinating mechanisms to share these inputs—important theoretical mechanisms that we posit in our theoretical analyses. In our empirical specifications, we also control for alternative bases of corporate relatedness such as product market relatedness or technological relatedness.

IO tables provide an excellent source of information to construct measures of relatedness. The input coefficients for an industry reflect how much of each of the inputs used in the product is required to produce a dollar's worth of output in the focal industry. Furthermore, the expenditures captured in the input coefficients are comprehensive in that they reflect all payments for inputs flowing from supplying industries to the focal industry, whether they be for capital goods or raw materials. Therefore, the combined input coefficients for an industry, or the industry's input profile, present a detailed and comprehensive account of the relationship between the focal industry and all other industries. Converting the differences in input profiles between two industries into a distance measure thus provides an opportunity to encapsulate the similarities between industries on multiple dimensions into a single-dimensional scale.[4]

We construct the input-relatedness measure in three steps:

Step 1. *Measuring the dyadic relatedness between any two businesses, i and j*: We use the data from the IO table to measure the similarity in input profiles between any two manufacturing businesses i and j. For this purpose, we employ a logic similar to the one used in Robins and Wiersema (1995). For any SIC—say, SIC i—we construct a vector of numbers, I_i, where the numbers correspond to the inputs directly required to create one dollar's worth of output in i. In other words, $I_i = \langle A_i, B_i, \ldots \text{for all other inputs} \ldots \rangle$, where A_i denotes the amount of input from industry A required to produce one dollar's worth of output in manufacturing industry i. Similar to the logic followed in Robins and Wiersema (1995), we calculate the relatedness between industries i and j, $DyadRel_{i,j}$, as the angular distance between the two vectors, I_i and I_j; i.e., $DyadRel_{i,j} = I_i \cdot I_j / (\|I_i\| \cdot \|I_j\|)$.

Step 2. *Measuring the relatedness of industry i with all other businesses of the firm k*: For each manufacturing industry i of a firm k, we calculate how related i is to all other manufacturing industries of the firm k. To do this, we calculate the weighted average relatedness of i with all other industries of the firm using the sales of other industries as the weights (i.e., the relatedness with the other industry has more weight if the other industry generates more sales for the firm). In other words,

$$R_{i,k} = \left(\sum_{j \neq i} Sales_j \times DyadRel_{i,j}\right) \Big/ \sum_{j \neq i} Sales_j.$$

Step 3. *Calculating firmwide input-relatedness*: We now use the measure calculated in Step 2 to calculate the overall input-relatedness of the firm. To do this, we construct the weighted average of the above measure, i.e., $R_{i,k}$ for all i in the firm k, using the sales of i as weights (i.e., the relatedness of a business to the rest of the firm has greater weight if the business generates more sales for the firm):

$$Input\_Rel_k = \left(\sum_i Sales_i \times R_{i,k}\right) \Big/ \sum_i Sales_i.$$

We use this measure, $Input\_Rel_k$, as our measure of the relatedness of the businesses of a firm k. It measures how much, on average, a manufacturing business of a firm k is related to all its other manufacturing businesses, taking into account the relative importance of the business to the firm. We mean-deviate the *Input-relatedness* and *Total oil dependence* measures to reduce collinearity.

Control Variables. Firms could also be relatedly diversified through their use of similar technologies or product markets. To control for these bases of relatedness, we include a measure of the degree to which the technologies underlying the businesses of the firm are related to each (*Technological relatedness*), based on Robins and Wiersema (1995), and the entropy measure that captures how diversified a firm is in the product markets based on its presence in different SIC codes (*Product-market diversification*). The entropy measure may, however, be sensitive to the domination of a single business in the firm (Robins and Wiersema 2003). Thus, we also include as an additional control the *Number of businesses* in a firm's portfolio.

A firm's investments in energy technologies could depend on the size of its innovative effort. We include controls for lagged research expenses in (*R&D expense*) as well as the total number of patents produced by the firm that year, *nTotalPat*; this includes the number of energy patents (paradigm-changing + paradigm-deepening) as well as the nonenergy patents. To control for firm size, we include measures of total *Sales* and net *Capital stock* value of the net property, plant, and equipment of the firm (these variables and *R&D expense* are used in logged form to scale their values). To control for unobserved heterogeneity, we construct the *Presample dependent variables*; we calculate these variables in the same way as the dependent variables except that the patents used are those that were applied for between 1976 and 1980, both years included.

A firm's investments in these technologies may also be affected by its ability to transfer the increased costs from the input shock to the customer. Thus, we include the lagged values of *Advertising expense* for the firm as a control. We also control for the slack available to a firm by including the *Liquidity* ratio (current assets/current liabilities), *Equity to debt* ratio, and *Profitability* (net income/total assets) variables. We use interpolated data for missing values in lagged *R&D*. Environmental conditions such as munificence can insulate the firm, reducing its sensitivity to the oil shock. We thus control for a number of environmental variables. Following the procedure described in Dess and Beard (1984), we use the data from the Census Bureau's Census of Manufacturers and Annual Survey of Manufacturing files and obtain the regression slope of sales, price-cost margin (PCM), and employment on time divided by their means over previous years as measures of environmental munificence. We use lagged values for these variables.

Results

Table 1 presents the correlations of the key variables used to test the hypotheses. Hypothesis 1 predicts that the greater the degree of relatedness in a firm's businesses, the greater are its investments into paradigm-changing technologies in response to the oil shock. We test H1 by examining the impact of the oil shock on *nParadigm-ChangingPat*. To control for firm size and the magnitude of innovative effort, we had identified two possible measures each (*Sales* and *Capital stock* for size and *nTotalPat* and *R&D expense* for magnitude of innovative effort). To limit multicollinearity issues, we use only one of the variables for each of these effects in our primary specification (*Sales* and *nTotalPat*); in sensitivity models detailed later, we include the alternative measures. Table 2 presents the results of this negative binomial regression with standard errors clustered by firm. Model 1 includes the control variables, Model 2 adds the *Total oil dependence* and *Input-relatedness* variables, and Model 3 adds the interaction between the *Total oil dependence* and *Input-relatedness* variables. The positive and significant coefficient of the interaction term of *Total oil dependence* and *Input-relatedness* shows that a firm's investments into paradigm-changing technologies that seek to substitute oil with alternative sources of energy in response to oil shock increase as the relatedness of the firm's businesses increases. We use the coefficients from Model 3 to evaluate the marginal effect of an increase in oil dependence at different levels of relatedness. Using the STATA "margins" command, we calculate the semielasticity with respect to *Total oil dependence*. For this computation we kept the covariates (except *Input-relatedness*) at their means and computed the impact of changing *Total oil dependence* at different values of *Input-relatedness*. The tests show that if the *Input-relatedness* is at the 25th percentile, a unit increase in *Total oil dependence* is associated

Table 1 Correlations

Variable	Mean	S.D.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) *nParadigm-ChangingPat*	0.3726	1.5647	1.0000								
(2) *nParadigm-DeepeningPat*	0.3080	0.9532	0.5216	1.0000							
(3) *Input-relatedness*	0.3127	0.1467	−0.1078	0.0241	1.0000						
(4) *Total oil dependence*	3.8179	7.5404	0.2264	0.0002	−0.4055	1.0000					
(5) *Presample nParadigm-ChangingPat*	3.8821	12.0063	0.5966	0.2403	−0.2394	0.4871	1.0000				
(6) *Presample nParadigm-DeepeningPat*	2.3308	6.4902	0.2400	0.6251	0.0823	−0.0644	0.2174	1.0000			
(7) *Technological relatedness*	0.0820	0.0709	0.0411	0.1365	0.2272	−0.2463	−0.0475	0.2267	1.0000		
(8) *Product-market relatedness*	2.1546	0.6697	0.1598	0.1764	−0.0350	−0.1187	0.0060	0.1584	−0.1271	1.0000	
(9) *Number of businesses*	39.2662	20.6478	0.3676	0.3408	−0.1469	0.1848	0.3548	0.4041	−0.0470	0.7702	1.0000
(10) *Advertising expense*	140.2411	215.7099	−0.1231	0.0156	−0.1478	−0.1597	−0.1127	0.2529	0.0939	−0.0905	−0.0683
(11) *Liquidity*	1.8041	0.6305	−0.1734	−0.1700	0.1238	−0.2383	−0.2009	−0.2376	0.0928	−0.0222	−0.1900
(12) *Profitability*	0.0604	0.0533	0.0130	0.0176	−0.0331	−0.0230	0.0233	−0.0087	0.0571	−0.0413	−0.0958
(13) *Equity to debt*	1.0392	0.5083	−0.1187	−0.0999	0.1145	−0.1303	−0.0821	−0.1480	0.0681	−0.1416	−0.2732
(14) *nTotalPat*	93.8061	132.7493	0.2956	0.5530	0.0387	−0.0478	0.3345	0.6998	0.2566	0.1109	0.3305
(15) *logR&D* (interpolated)	4.2073	3.1449	0.1350	0.1800	0.1151	−0.0135	0.1841	0.2409	0.2068	−0.0829	0.0319
(16) *logSales*	8.5758	0.8266	0.3643	0.3438	−0.1546	0.3152	0.5875	0.5143	0.1659	−0.0124	0.3974
(17) *logCapitalStock*	7.3813	0.9804	0.2756	0.2825	−0.2270	0.4050	0.5401	0.4146	−0.1378	−0.0278	0.3472
(18) *Sales growth*	0.1363	0.5250	0.0751	−0.0614	−0.1287	−0.0752	0.0307	−0.1541	0.1814	−0.0525	−0.1299
(19) *PCM growth*	0.0891	0.5314	0.0638	−0.0619	−0.1408	−0.0715	0.0196	−0.1747	0.1955	−0.0401	−0.1384
(20) *Employee growth*	0.0922	0.4750	0.0802	−0.0557	−0.1193	−0.0740	0.0378	−0.1574	0.2151	−0.0531	−0.1190

Table 1 (cont'd)

Variable	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)
(10) *Advertising expense*	1.0000									
(11) *Liquidity*	−0.1330	1.0000								
(12) *Profitability*	0.1640	0.2711	1.0000							
(13) *Equity to debt*	−0.0820	0.6841	0.4422	1.0000						
(14) *nTotalPat*	0.1654	−0.1062	0.0804	0.0557	1.0000					
(15) *logR&D* (interpolated)	0.1008	−0.1017	0.0979	−0.0320	0.3942	1.0000				
(16) *logSales*	0.3560	−0.3324	0.1008	−0.1748	0.5972	0.3267	1.0000			
(17) *logCapitalStock*	0.2516	−0.4146	−0.0592	−0.1840	0.5476	0.2335	0.8458	1.0000		
(18) *Sales growth*	−0.0587	0.0137	0.2036	0.0230	0.0405	0.1369	−0.0669	−0.1199	1.0000	
(19) *PCM growth*	0.0398	0.0484	0.2837	0.0470	0.0279	0.1459	−0.0380	−0.1372	0.9432	1.0000
(20) *Employee growth*	−0.0733	0.0415	0.1796	0.0096	0.0177	0.1556	−0.0713	−0.1580	0.9390	0.8893

with an approximately 14.26% increase in the number of paradigm-changing patents; this almost doubles to 29.04% when the *Input-relatedness* is at the 75th percentile. This provides evidence supporting our hypothesis that higher levels of relatedness will foster more effort into paradigm-changing innovations.

In Model 4 we include the alternative measure of the control for size (*Capital stock*). In Model 5 we include *R&D expense* (an alternative measure of magnitude of innovation efforts) using only those observations for estimation for which we have R&D data. The number of observations drops sharply because of missing values in R&D. In Model 6 we include the variable *R&D expense* with values imputed using the STATA "ipolate" command to recover some of the missing observations (those that were imputable per STATA). Since the environmental variables are highly correlated, we also report the results of including them one at a time in Models 7–9. As Table 2 indicates, in Models 4–9, the results are substantively similar to those in Model 3 (our base results).

In H2, we predict that when firms face the oil shock, firms whose businesses are less related to each other are more likely to respond technologically by increasing their investments in paradigm-deepening technologies. The negative binomial specification with *nParadigmDeepeningPat* as the dependent variable tests this prediction. We follow the same sequence of models as in Table 2. Table 3 reports the results of the regression for this "paradigm-deepening" regression (with clustered errors). Model 1 includes the control variables, Model 2 adds the *Total oil dependence* and *Input-relatedness* variables, and Model 3 includes the interaction of the *Total oil dependence* and *Input-relatedness* variables. The negative and significant coefficient of the interaction term between *Total oil dependence* and *Input-relatedness* provides support for H2. In Models 4 and 5 we include the alternative measures of the controls for size (*Capital stock*) and magnitude for innovation effort (*R&D expense*), with the latter being estimated only for observations for which we had *R&D expense*. In Model 6 we include the variable *R&D expense* with values imputed using STATA "ipolate" command to recover some of the missing observations (those that were imputable per STATA). Since the three environmental variables were highly correlated with each other, Models 7–9 report the results from specifications including one environmental variable at a time.

The results from Models 4–9 are substantively similar to our basic specification (Model 3). We use the coefficients from Model 3 to evaluate the marginal effect of an increase in oil dependence at different levels of relatedness. As before, we use the STATA "margins" command to calculate the semielasticity with respect to *Total oil dependence*. The tests show that if *Input-relatedness* is at the 25th percentile, a unit change in *Total oil dependence* is associated with an about −18% change in the number of paradigm-changing patents; this almost doubles to −35.5% when the *Input-relatedness* is at the 75th percentile.

We did not present any hypothesis on this main effect of oil dependence. However, we note that the coefficient of *Total oil dependence* for paradigm-deepening innovation is negative and significant, although the coefficient on the same variable is positive for paradigm-changing innovation. This suggests that higher levels of oil dependence are associated with decreased paradigm-deepening innovation (but increased paradigm-changing innovation). One possible explanation of this finding is that for firms that are very highly oil dependent, the marginal benefits that emerge through paradigm-deepening innovations are not considered significant enough to "move the needle," given their level of dependence, and thus few investments are made in this direction. Rather, in such firms the focus shifts to paradigm-changing innovation, as that may provide a more fundamental solution to this problem. Such a tendency would also be consistent with our earlier argument that paradigm-changing innovation may substitute for paradigm-deepening innovation at least for some firms. In-depth exploration of this question, however, is beyond the scope of our paper, given the data limitations, and hence is a task that we leave for future research.

Table 2 Paradigm-Changing Innovations: Negative Binomial with Clustered Errors

	Model								
Variable	1	2	3	4	5	6	7	8	9
Input-relatedness		−0.915	−0.164	−0.179	−0.667	−0.476	1.119	1.003	1.120
		(1.848)	(2.323)	(2.226)	(2.240)	(2.305)	(1.990)	(1.939)	(2.079)
Total oil dependence		0.044	0.224*	0.214*	0.220*	0.239*	0.195*	0.188*	0.204*
		(0.027)	(0.089)	(0.086)	(0.098)	(0.099)	(0.081)	(0.079)	(0.085)
Input-relatedness × *Total oil dependence*			0.785**	0.732*	0.771**	0.834**	0.750**	0.729**	0.764**
			(0.334)	(0.351)	(0.329)	(0.337)	(0.285)	(0.285)	(0.300)
Presample nParadigm-ChangingPat	0.044	0.050	0.033	0.050*	0.028	0.029	0.029	0.029	0.027
	(0.028)	(0.029)	(0.026)	(0.022)	(0.026)	(0.025)	(0.021)	(0.022)	(0.022)
Technological relatedness	6.260*	9.174***	11.147***	13.188***	10.196***	10.006***	9.823**	10.066**	9.308**
	(2.595)	(2.726)	(2.871)	(3.101)	(2.448)	(2.651)	(3.071)	(3.219)	(2.864)
Product market relatedness (entropy)	1.274	1.865*	1.879*	1.515	1.947**	1.872*	1.209	1.087	1.356
	(0.684)	(0.824)	(0.826)	(0.844)	(0.740)	(0.793)	(0.842)	(0.847)	(0.817)
Number of businesses	−0.012	−0.030	−0.024	−0.015	−0.023	−0.022	−0.007	−0.005	−0.009
	(0.024)	(0.028)	(0.026)	(0.026)	(0.025)	(0.025)	(0.025)	(0.025)	(0.025)
Advertising expense	−0.004	−0.003	−0.004	−0.003	−0.004	−0.004	−0.004	−0.004*	−0.004
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.002)	(0.002)	(0.002)
Liquidity	−1.397*	−1.263*	−1.211*	−1.315*	−1.254	−1.271	−0.927	−0.884	−0.985
	(0.632)	(0.594)	(0.605)	(0.568)	(0.659)	(0.666)	(0.579)	(0.578)	(0.582)
Profitability	3.734	5.549	7.197	10.804*	6.303	6.874	3.565	3.730	3.596
	(4.364)	(5.072)	(4.990)	(4.889)	(4.696)	(4.739)	(4.816)	(4.733)	(4.970)
Equity to debt	−0.655	−1.009	−1.220	−1.428	−1.071	−1.145	−1.208	−1.263	−1.130
	(0.845)	(0.949)	(0.879)	(0.856)	(0.849)	(0.865)	(0.909)	(0.926)	(0.903)
nTotalPat	0.002	0.003	0.003	0.004	0.002	0.003	0.002	0.002	0.002
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
logR&D[a]					−0.035	0.149			
					(0.388)	(0.163)			
logSales	0.946	0.774	1.147		1.284	1.034	1.179	1.149	1.257
	(0.629)	(0.650)	(0.683)		(0.846)	(0.697)	(0.634)	(0.629)	(0.665)
logCapitalStock				0.470					
				(0.493)					
Sales growth	−0.313	−0.560	0.099	−0.034	0.309	0.362	0.756		
	(1.894)	(1.968)	(2.333)	(2.535)	(2.239)	(2.230)	(0.443)		
PCM growth	−1.932	−2.986*	−3.278*	−3.427*	−3.699**	−3.743**		0.609	
	(1.115)	(1.293)	(1.425)	(1.478)	(1.388)	(1.403)		(0.453)	
Employee growth	3.133	4.606**	4.330*	4.682*	4.561*	4.404*			1.145*
	(1.638)	(1.786)	(1.850)	(1.969)	(1.867)	(1.784)			(0.500)
Constant	−10.681	−10.462	−13.857*	−7.141	−14.943*	−13.364*	−13.016*	−12.523*	−13.963*
	(6.140)	(6.116)	(6.456)	(4.442)	(7.009)	(6.432)	(5.944)	(5.891)	(6.280)
Log pseudo-likelihood/observations	−99.85/264	−98.58/263	−95.98/263	−97.26/263	−94.74/240	−95.07/253	−98.58/263	−99.04/263	−97.83/263
Wald χ^2 vs. previous model		2.93 (2)	5.54* (1)						

Notes. Standard errors are in parentheses. Single-tailed tests were used for hypothesized variables; year dummies are included in all models.

[a]Interpolated in Model 6.

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

Discussion and Conclusion

We examined the impact of a firm's diversification on its technological response to shocks. We found that increasing relatedness across businesses disposes firms to favor investments into paradigm-changing technologies in response to the oil shock, whereas increasing unrelatedness between their businesses disposes firms to invest more into paradigm-deepening technologies. Although we used the oil-shock context, the arguments developed apply more broadly because replacing an old paradigm

Table 3 Paradigm-Deepening Innovations: Negative Binomial with Clustered Errors

	Model								
Variable	1	2	3	4	5	6	7	8	9
Input-relatedness		−1.503 (1.236)	−3.560** (1.317)	−3.609** (1.356)	−3.825** (1.403)	−3.969** (1.443)	−3.965** (1.296)	−3.942** (1.321)	−3.853** (1.300)
Total oil dependence		−0.021 (0.024)	−0.276* (0.125)	−0.293* (0.137)	−0.225 (0.132)	−0.226 (0.134)	−0.313* (0.132)	−0.323* (0.138)	−0.314* (0.134)
Input-relatedness × *Total oil dependence*			−0.927* (0.437)	−1.003* (0.470)	−0.811* (0.439)	−0.820* (0.451)	−1.043* (0.463)	−1.085* (0.484)	−1.045* (0.468)
Presample nParadigm-DeepeningPat	0.104* (0.049)	0.105* (0.046)	0.096* (0.047)	0.094* (0.047)	0.105* (0.045)	0.106* (0.044)	0.095* (0.046)	0.094* (0.047)	0.098* (0.045)
Technological relatedness	0.715 (2.658)	1.111 (2.479)	0.184 (2.491)	1.028 (2.988)	0.099 (2.725)	0.052 (2.747)	0.364 (2.455)	0.216 (2.474)	0.201 (2.524)
Product-market relatedness (entropy)	−0.043 (0.463)	−0.085 (0.472)	−0.159 (0.480)	−0.284 (0.453)	−0.270 (0.462)	−0.283 (0.465)	−0.185 (0.481)	−0.160 (0.485)	−0.186 (0.483)
Number of businesses	−0.002 (0.018)	−0.003 (0.018)	0.001 (0.018)	0.006 (0.016)	0.007 (0.016)	0.008 (0.016)	0.001 (0.018)	0.001 (0.018)	0.001 (0.018)
Advertising expense	−0.003** (0.001)	−0.004*** (0.001)	−0.004** (0.001)	−0.003** (0.001)	−0.004** (0.001)	−0.004** (0.001)	−0.004*** (0.001)	−0.004*** (0.001)	−0.004*** (0.001)
Liquidity	0.267 (0.329)	0.187 (0.324)	0.138 (0.317)	0.134 (0.335)	0.132 (0.338)	0.137 (0.337)	0.187 (0.306)	0.204 (0.306)	0.217 (0.300)
Profitability	3.492 (2.963)	3.372 (2.936)	2.508 (2.809)	3.593 (2.891)	2.222 (2.714)	2.253 (2.739)	2.325 (2.699)	2.292 (2.653)	1.685 (2.652)
Equity to debt	−0.592 (0.507)	−0.531 (0.497)	−0.484 (0.487)	−0.518 (0.507)	−0.611 (0.558)	−0.615 (0.562)	−0.547 (0.468)	−0.546 (0.473)	−0.543 (0.486)
nTotalPat	0.003 (0.002)	0.003 (0.002)	0.003 (0.002)	0.003 (0.002)	0.002 (0.002)	0.002 (0.002)	0.003 (0.002)	0.003 (0.002)	0.002 (0.002)
logR&D[a]					0.556** (0.216)	0.579** (0.212)			
logSales	0.369 (0.331)	0.435 (0.343)	0.380 (0.331)		−0.294 (0.378)	−0.305 (0.376)	0.426 (0.328)	0.426 (0.326)	0.458 (0.325)
logCapitalStock				0.224 (0.357)					
Sales growth	−2.167 (1.117)	−2.111 (1.148)	−1.722 (1.109)	−1.961 (1.114)	−1.227 (1.115)	−1.154 (1.125)	−0.457 (0.291)		
PCM growth	0.521 (0.816)	0.616 (0.836)	0.351 (0.851)	0.399 (0.890)	−0.024 (0.834)	−0.081 (0.832)		−0.429 (0.303)	
Employee growth	1.602 (1.243)	1.328 (1.246)	1.132 (1.217)	1.359 (1.223)	0.645 (1.331)	0.607 (1.347)			−0.395 (0.357)
Constant	−5.213 (3.124)	−5.536 (3.091)	−5.268 (3.007)	−3.749 (2.821)	−1.915 (2.859)	−1.937 (2.875)	−5.635 (3.002)	−5.764 (3.005)	−5.911* (2.988)
Log pseudo-likelihood/ observations	−127.6/264	−127.0/263	−125.8/263	−126.3/263	−118.8/240	−119.1/253	−126.3/263	−126.5/263	−126.7/263
Wald χ^2 vs. previous model		1.65 (2)	4.5* (1)						

Notes. Standard errors are in parentheses. Single-tailed tests were used for hypothesized variables; year dummies are included in all models.
[a]Interpolated in Model 6.
*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

with a new one almost always involves making extensive changes in the surrounding technoeconomic system. For instance, if there was a shock with respect to other broadly used, generic inputs such as steel, aluminum, copper, basic chemicals, etc., similar considerations would inform the firms' R&D decisions to choose between finding ways of using the material more efficiently or finding substitutes.

Our study connects to three literatures. First, it contributes to the technological evolution literature by drawing attention to the considerations involved in switching from one technological paradigm to another, and it identifies the relatedness between a firm's businesses as a key influence in its willingness to invest in the new paradigm. Second, it contributes to the diversification literature: it suggests a need to study not just the impact of firm scope on firm performance, as has long been done in the strategy literature, but also the impact of firm scope on firm behavior. Third, it contributes to the induced innovation literature by identifying firm-level factors that moderate the inducements provided by the external environment to invest in a certain technological direction. We touch on each of these contributions next.

The technology evolution literature has developed an integrative "technological paradigms" model that brings together the role of consumers (who want new goods), the supply environment (in the form of science and technology availability), and incentives (appropriability conditions) in driving the rate and direction of technical change (Cohen and Levin 1989, Nightingale 2008, Teece 2008). In this model, however, there is a limited role for firms—they are somewhat passive "readers of signals" about consumer wants that they then translate into products and revenues by harnessing the science and technology knowledge available, conditional on the appropriability conditions (Dosi 1988, Teece 2008). The model is silent on what role firms play in the emergence of competitive paradigms that may eventually supplant the existing dominant paradigms.

Consistent with the technology paradigms model's focus on incentives, firms enter the picture on technological paradigm change through their role as incumbents or entrants or as progenitors of breakthrough or radical innovation (Tushman and Anderson 1986). In this paper we push this thought process forward on two dimensions. First, we explicitly focus on differences between incumbents' diversification profiles as the source of differential investment behavior, rather than the differences between incumbents and entrants. We thereby suggest that the rate and direction of change in technology depends not only on the distribution of incumbents and entrants in an industry but also on the diversity in the composition of incumbents in the industry.

We also broaden the focus of study from individual breakthrough inventions to technological paradigms that involve not just individual or even clusters of inventions but a joint consideration of the *technology of technical change* and the *commerce of technical change*. This broadening highlights the fact that switching from one technology to another is far more complex than the terms "factor-saving" and "factor-substituting" technical change would lead us to believe. For economists, the factor-saving and factor-substituting abstraction is analytically valuable. For managers, however, it underplays the complexity and magnitude of their task in switching from one regime to another, a difficulty that we highlight using the paradigm-changing and paradigm-deepening terminology.

Although this distinction between paradigm-changing and paradigm-deepening that we introduce is related to a well-established distinction between competence-enhancing and competence-destroying technical change (Tushman and Anderson 1986), it is nevertheless conceptually distinct. The competence-enhancing versus competence-destroying typology characterizes technical change in terms of its implications for incumbent firms. Our typology characterizes technical change in terms of its implications for incumbent technologies (or more specifically, technological paradigms). Since firms can simultaneously invest in multiple technological paradigms, there is no one-to-one match between paradigm changing and competence destroying or paradigm deepening and competence enhancing, and vice versa. A set of paradigm changing technical changes could be simultaneously competence destroying for one set of incumbents and competence enhancing for another. For instance, electric cars represent a new paradigm with respect to automotive technology, where gasoline-powered cars represent the incumbent paradigm. Yet electric cars are not necessarily competence destroying from the perspective of General Motors (GM)—indeed, GM is one of the leaders in electric car development.

Another literature (e.g., Karim and Mitchell 2000) investigates firms' engagement in path-deepening versus path-breaking change. This distinction also differs from ours on multiple counts. Path-breaking and path-deepening change focuses on a different referent unit and different loci of action and attention; the literature defines an organizational change to be path-breaking or deepening in relation to a particular firm, rather than in relation to an incumbent or emerging technology. A change is path breaking when it entails the postacquisition retention of product-lines new to the firm; path-deepening change refers to the postacquisition retention of product lines overlapping with the firm (Karim and Mitchell 2000). Path-changing refers to actions that are "new" to the firm; paradigm-changing refers to a paradigm that is relatively new to the world. Thus, changes can be simultaneously path deepening and paradigm changing (or not), depending on the firm's prior investments. Furthermore, the considerations for investing in path-deepening versus path-changing changes focus largely on activities within the firm; however, a technological paradigm exists largely because of its acceptance and use by a broad set of players outside the firm. Thus, the factors to be considered in analyzing path-deepening versus paradigm-deepening change would be quite distinct.

Our study also contributes to the diversification literature by pointing to the influence of diversification on a firm's *behavior* or conduct; in contrast, the extant literature has extensively studied the effect of diversification on a firm's *performance* (Ramanujam and

Varadarajan 1989). The results collectively show that firms with different degrees of relatedness between their businesses react differently to the same shock. The diversification-performance literature has argued that heterogeneity in firm performance can be systematically linked to the relatedness of their portfolios. This study draws attention to two distinct reasons for such performance differentials. First, managers in firms with unrelated businesses do the same things as their counterparts in firms with related businesses, but they just execute them more poorly. Alternatively, as this paper's results suggest, perhaps related and unrelated diversifiers might perform differently because they choose to do different things in response to their environment. Indeed, prior investments that different firms have made in their organizational processes, structures, and systems based on the relatedness of their businesses may alter what the optimal strategy for each firm is in the face of a shock or stimulus. In our context we find that the prior commitments of firms to different business portfolios drove them to different responses to the oil shock. This basic intuition could be explored in conjunction with other stimuli that influence firm strategies to provide a clearer understanding of whether the differences in performance of firms with unrelated businesses versus related businesses is due to poor execution of their chosen strategies or because they have chosen different strategies. Further research would help to illuminate this conjecture.

We also make an empirical contribution to the diversification literature by developing a measure of relatedness of a firm's businesses that comprehensively captures the underlying similarities between businesses from an input perspective. Although no single measure of diversification is likely to be perfect, this measure addresses some of the weaknesses of other currently used measures. The IO-based measure is more comprehensive than measures that focus on single input (e.g., technology) to characterize a firm's relatedness profile. The IO coefficients capture the total inputs into a focal industry from all other industries, hence providing a more broad-based measure of the relatedness of the focal industry with other industries. The IO-based measure is also empirically grounded, relative to other measures. IO coefficients are based on the actual volume of input flows across industries, in contrast to being imposed by a hierarchical logic that is assumed to reside in the SIC system (as, for instance, is assumed in entropy-based measures). Comparing these input profiles across industries thus enables a measure that provides a detailed evaluation of how similar an industry's businesses are in their inputs, processes, and dependencies on other industries. This should be helpful in providing a proxy for the extent of strategic relatedness between the businesses of a multidivisional firm.

Finally, from the perspective of the research on induced innovation, our study highlights the fact that the aggregate response of an economy or a sector in a free market system will depend on the composition of the actors in that system. For instance, our findings suggest that in an economy characterized by unrelated diversifiers, the supplanting of existing technological paradigms by external inducements may be more difficult than in an economy in which firms are relatedly diversified. In the induced innovation literature, the focus has often been on evaluating sectoral responses to changes in input prices (Liu and Shumway 2009). Yet the results of this paper suggest that within a sector, the characteristics of different firms may lead to differential responses to the shock. Hence, aggregating across their responses to measure a sectoral response may not present an accurate picture of the underlying microdynamics. This suggests that rich insights could come from exploring how the underlying composition of firms may lead to different aggregate effects in different economies.

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Endnotes
[1]http://elsa.berkeley.edu/~bhhall/bhdata.html, accessed May 2008.
[2]We thank an anonymous reviewer for drawing attention to this limitation and for encouraging us to think more closely about the problem.
[3]The classes/subclasses are listed in the appendix of Popp's (2006) paper; the appendix can be found at the following website: http://faculty.maxwell.syr.edu/dcpopp/papers/TheyDontCiteAppendix.pdf (accessed December 2008).
[4]We thank an anonymous reviewer for providing a suggestion that led to this measure.

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