Radical Innovation: Literature Review and Development of an Indicator

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Abstract

This paper presents the genesis of radical innovation literature and illustrates how both small and large firms, to differing degrees, generate radical innovation. It then distinguishes the characteristics of incremental versus radical innovation. The paper goes on to demonstrate how scholars often contradict their findings by describing how large firms or small firms innovate or how small firms innovate more and, finally, suggests using a much needed quantifiable identification metric, in both *ex ante* and *ex post* analysis, the Dahlin-Behrens model of radical identification.

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1. Introduction

Since the early days of Joseph Schumpeter in the 1920s, the concept of radical innovation in economic theory has been a driving force for economic growth. Yet the term offers an abundance of concepts and definitions that can be difficult for policy-makers and scholars hoping to identify *ex ante* radical innovations to expedite and facilitate growth. Building a universal and compelling concept and methodology to identify radical innovation remains elusive and problematic for scholars for several reasons. First, terminology of the definition has varied from really new to breakthrough, discontinuous, generational and, finally, radical innovation. The differing etymology is, in part, due to the differing fields of research involved in the study of radical innovation. The differing terms each carry the spirit of what radical innovation creates, yet they are unable to provide a unifying foundation for distinguishing radical innovation.

The second problem relates to the difficulty associated with quantifying or recognizing what actually constitutes a radical innovation *ex ante*, (the famous "I know it when I see it issue") Traditionally, policy-makers and scholars have been unable to identify nascent radical innovations *ex ante*. Given the difficulty of identifying innovations *ex ante*, how can one aggregate radical innovations' contribution to economic growth for a region or country? For this reason, most scholars have left the definition abstract and instead have focused their research on the concept and the *ex post* impact of singular fields of radical innovative activity.

This paper will define innovation and provide a brief description of and distinction between radical innovation and incremental innovative activity. It then applies the Dahlin and Behrens (2005) heterogeneous classifications of radical innovations found in the literature. The classifications identify the different forms of radical innovation that are found in the literature. Finally, the paper offers conclusions and suggestions to identify radical innovations *ex ante* in a uniform manner.

2. Origins of Radical Innovation

The concept of innovation, at least implicitly, dates back at least to Joseph Schumpeter's seminal 1934 treatise, *The Theory of Economic Development; and Inquiry into Profits, Capital, Credit, Interest and the Business Cycle*. His term, the "process of creative destruction," conceptually and literally began a radical revolution in economic theory and commercial orientation. The process, as Schumpeter argued, was one where large firms were destroyed by the entrepreneur who seizes commercial opportunities from inventors. Entrepreneurs enter the market with such commercial competitive advantages, due to their potential innovations, that they not only compete but "destroy" incumbent firms and their respective economies of scale due to the entrepreneur's superior innovation. Schumpeter's work on creative destruction created the foundation for innovation.

As McCraw (2007) points out, at the centre of Schumpeter's intellectual contribution was a focus on innovation. Schumpeter, more than any of the great economists before him, viewed innovation as the driving force of progress and development. But Schumpeter also emphasized that innovation, and therefore economic progress, comes at a price — creative destruction. Just as the factory wiped out the blacksmith shop and the car superseded the horse and buggy, incumbents will be displaced by innovating entrepreneurs. As McCraw (2007, p. 6) concludes about Schumpeter, "He knew that creative destruction fosters economic growth but also that it undercuts cherished human values. He saw that poverty brings misery but also that prosperity cannot assure peace of mind."

Schumpeter did not distinguish explicitly between radical innovation and other types of innovative activity, however. While one may infer that Schumpeter's creative destruction replaces old technologies and expands new commercial opportunities, the concept of radical innovation must refer to a much more specific type of innovation that is traditionally identified in *ex post* analysis.

Along with Schumpeter, many other scholars applied *ex post* identification of radical innovations for their empirical investigation. This method, however, creates several problems for both scholars as well as policy-makers. As will be discussed below, *ex post* identification causes two problems. Firstly, in a practical sense, one would ideally wish to identify an emerging radical innovation at an early stage in order to expedite commercial entry into the market. Secondly, and more importantly, studies based on *ex post* analysis have inherent methodological problems. According to Dahlin and Behrens (2005, p. 718), "basing identification of radical inventions on market success by only including innovations in a study, for instance, ignoring inventions that never reach the market, creates a selection bias; indeed, technologies might be radical in a technological sense without having significant market impact, since the market impact of a technology is affected by many non-technological conditions."

2.1 Firm Size and Radical Innovations

In order to understand where radical innovations originate, we will first offer a brief summary of radical innovations to better understand how heterogeneous the sources of radical innovations are.

Small Firm Entrepreneurship

As illustrated in Table 1, radical innovations delivered by small firm entrepreneurs up until 1995 are substantial. Since 1995, many new drivers of economic growth have emerged; for example, information technology (e.g. Microsoft, Dell, Skype and eBay) and renewable resource technology (hybrid motor, wind technology) have been placed on the impressive list. While there is no empirical investigation of how the radical technologies were developed, one can *ex post* immediately appreciate their value-added to economies.

Table 1 Radical Innovations from Small Firm Entrepreneurs

Air conditioning	Heart valve	Pre-stressed concrete
Air passenger service	Heat sensor	Prefabricated housing
Airplane	Helicopter	Pressure-sensitive tape
Articulated tractor chassis	High-resolution CAT scanner	Programmable computer
Cellophane artificial skin	High-resolution digital X-ray	Quick-frozen food
Assembly line	High-resolution X-ray microscope	Reading machine
Audio tape recorder	Human growth hormone	Rotary oil drilling bit
Bakelite	Hydraulic brake	Safety razor
Biomagnetic imaging	Integrated circuit	Six-axis robot arm
Biosynthetic insulin	Kidney stone laser	Soft contact lens
Catalytic petroleum cracking	Large computer	Solid fuel rocket engine
Computerized blood pressure controller	Link trainer	Stereoscopic map scanner
Continuous casting	Microprocessor	Strain gauge
Cotton picker	Nuclear magnetic resonance scanner	Strobe lights
Defibrillator	Optical scanner	Supercomputer
DNA fingerprinting	Oral contraceptives	Two-armed mobile robot
Double-knit fabric	Outboard engine	Vacuum tube
Electronic spreadsheet	Overnight national delivery	Variable output transformer
Freewing aircraft	Pacemaker	Vascular lesion laser
FM radio	Personal computer	Xerography
Front-end loader	Phototypesetting	X-ray telescope
Geodesic dome	Polaroid camera	Zipper
Gyrocompass	Portable computer	Blackberry

Source: Baumol (2004)

Large Firm Innovation

The origins of radical innovations are more complex than the traditional belief of inventors in a garage coming up with a new idea. There are many cases where large and successful corporations have developed, implemented and profited from in-house radical innovations (e.g. Nokia and the cellphone; Kodak and the digital camera; Apple Computers and the iPhone). As illustrated in Table 2, there is a large field of radical innovation where large firms have invented and delivered products to the market.

Table 2 Radical Innovations from Large Firms

AM radio	Wireless Telegraph and Signal Co.
Analogue answering machine	American Telegraphone Co.
Analogue quartz watch	Seiko
Black-and-white celluloid roll camera	Eastman Dry Plate & Film Co.
Camcorder	Sony
Cassette tape player	Phillips
Compact disc player	Phillips and Sony
Cellular telephone	Motorola
Digital answering machine	Sharp
Digital camera	Sony
Digital high-definition television	Panasonic
Digital video disc (DVD) player	Toshiba
Disposable shaver	Bic Corp.
Electric blanket	General Electric
Electronic colour television	RCA
Electronic desktop calculator	Sharp
Laptop computer	Tandy Corp. (Radioshack)
Laser disc player	Phillips
Laser printer	IBM
Microwave	Raytheon
Mini-disc player	Sony
Palm computer	Amstrad

Source: Chandy and Tellis (2000)

2.2 Characteristics of Radical Innovation vis-à-vis Incremental Innovation

Dahlin and Behrens (2005) explicitly link the extent to which an *invention* is radical to the nature of the ideas upon which the innovative activity is based, and the extent to which the innovative activity involves information that is codified or knowledge that is inherently tacit in nature. Information refers to facts that can be codified and where the valuation across different agents, or employees, and layers of decision-making bureaucracy within the organization is relatively constant. Innovative activity based on economic information tends to be incremental in nature in that it generally involves an organizational consensus about the potential value and impact of the innovation. Thus, incremental innovation tends to support and enhance the status quo organization.

By contrast, radical innovation is based on knowledge involving tacit ideas that not only defy codification, but also whose economic value remains highly uncertain and asymmetric and tends to generate radical innovations. The expected value of any new idea is highly uncertain, and has a much greater variance than would be associated with innovative activity based on information. When it comes to radical innovation, there is uncertainty about whether the new producer service can be produced, how it can be produced, and whether sufficient demand for that visualized new product or service might actually materialize (Arrow, 1962).

In addition, new ideas constituting tacit knowledge are typically associated with considerable asymmetries. For example, in order to evaluate a proposed new idea concerning a new biotechnology product, the decision maker might not only need to have a PhD in biotechnology, but also a specialization in the exact scientific area. Differences in education, background and experience can result in divergence in the expected value of a new project or variance in the outcomes anticipated from pursuing that new idea, both of which can lead to divergence in recognition and evaluation of opportunities between economic agents and decision-making hierarchies. Such divergence in the valuation of new ideas will become even greater if the new idea is not consistent with the core competence and technological direction of the incumbent firm. Thus, radical innovation tends to be disruptive to the status quo organization and strategy of the firm.

In fact, what actually constitutes a radical innovation and distinguishes it from an incremental innovation may depend upon the question being asked and the perspective in which innovative activity is being considered. Table 3 presents a broad spectrum of perspectives on what distinguishes a radical innovation from an incremental innovation. For example, in terms of the time frame, the impacts of incremental innovations tend to be realized over a shorter time period than those of radical innovations. Similarly, the source and process of idea generation and opportunity recognition varies between incremental and radical innovations.

Table 3 Distinguishing between Incremental and Radical Innovations

Focus	Incremental Innovation	Radical Innovation
Time frame	Short term — 6 to 24 months	Long term — usually 10 years or more
Development strategy	Step by step from conception to commercialization, high levels of certainty	Discontinuous, iterative, setbacks, high levels of uncertainty
Idea generation and opportunity recognition	Continuous stream of incremental improvement; critical events largely anticipated	Ideas often pop up unexpectedly and from unexpected sources, slack tends to be required; focus and purpose might change over the course of development
Process	Formal, established, generally with stages and gates	A formal, structured process might hinder
Business case	A complete business case can be produced at the outset, customer reaction can be anticipated	The business case evolves throughout development and might change; predicting customer reaction is difficult
Players	Can be assigned to a cross-functional team with clearly assigned and understood roles; skill emphasis is on making things happen	Skill areas required; key players may come and go; finding the right skills often relies on informal networks; flexibility, persistence and willingness to experiment are required
Development structure	Typically, a cross-functional team operates within an existing business unit	Tends to originate in research and development (R&D); tends to be driven by the determination of one individual who pursues it wherever he or she is
Resources and skill requirements	All skills and competences necessary tend to be within the project team; resource allocation follows a standardized process	It is difficult to predict skill and competence requirements; additional expertise from outside might be required; informal networks; flexibility is required
Operating unit involvement	Operating units are involved from the beginning	Involving operating units too early can again lead to great ideas becoming small

Source: Stamm (2003)

3. Entrepreneurship, Radical Innovation and the Knowledge Filter

An important and broadly accepted strand of literature suggests that small and new firms will be at a competitive disadvantage with respect to generating innovative activity in general and radical innovations in particular. According to Griliches' (1979) model of the knowledge production function, innovative activity is the direct result of investments made by a firm in knowledge inputs, such as R&D and human capital. Since larger firms generally invest significantly more in R&D than small and new firms, they would be expected to generate more innovative activity.

Since radical innovation generates more value than incremental innovation, some scholars have assumed, and even developed elaborate theoretical models to explain why, large firms, which have large R&D departments, will generate more radical innovations than small and new firms, which are constrained by size in their ability to invest in R&D (Cohen and Klepper, 1992a, b).

Five factors favouring the innovative advantage of large enterprises have been identified in the literature. First is the argument that innovative activity requires a high fixed cost. As Comanor (1967) observes, R&D typically involves a "lumpy" process that yields scale economies. Similarly, Galbraith (1956, p. 87) argues, "Because development is costly, it follows that it can be carried on only by a firm that has the resources which are associated with considerable size."

Second, only firms that are large enough to attain at least temporary market power will choose innovation as a means for maximization (Kamien and Schwartz, 1975). This is because the ability of firms to appropriate the economic returns accruing from R&D and other knowledge-generating investments is directly related to the extent of that enterprise's market power (Levin et al., 1985, 1987; Cohen et al., 1987; Cohen and Klepper, 1991).

Third, R&D is a risky investment; small firms engaging in R&D make themselves vulnerable by investing a large proportion of their resources in a single project. However, their larger counterparts can reduce the risk accompanying innovation through diversification into simultaneous research projects. The larger firm is also more likely to find an economic application for the uncertain outcomes resulting from innovative activity (Nelson, 1959).

Fourth, scale economies in production may also provide scope economies for R&D. Scherer (1991) notes that economies of scale in promotion and distribution facilitate penetration of new products, enabling larger firms to enjoy greater profit potential from innovation. Finally, an innovation yielding cost reductions of a given percentage results in higher profit margins for larger firms than for smaller firms.

There is also substantial evidence that technological change, or rather one aspect of technological change, R&D, is, in fact, positively related to firm size. The abundance of empirical studies relating R&D to firm size is thoroughly reviewed in Acs and Audretsch (2003). The empirical evidence is generally consistent with the hypothesis that large firms invest in proportionately more R&D.

Using a direct measure of innovative output from the U.S. Small Business Administration's innovation data base, Acs and Audretsch (1990) and Pavitt et al. (1987), in a similar study for the U.K., show that the most innovative U.S. firms are large corporations. Furthermore, the most innovative American corporations also tend to have large R&D laboratories and be R&D intensive. At first glance, these findings, based on direct measures of innovative activity, seem to confirm the conventional wisdom. However, in the most innovative four-digit standard industrial classification (SIC) industries, large firms, defined as enterprises with at least 500 employees, contributed more innovations in some instances, while in other industries small firms produced more innovations. For example, in the area of computers and process control instruments, small firms contributed the bulk of innovations. By contrast, in the area of pharmaceutical preparation and aircraft industries, large firms were much more innovative.

Probably the best measure of innovative activity is the total innovation rate, which is defined as the total number of innovations per thousand employees in each industry. The innovation rate for large firms is defined as the number of innovations made by firms with at least 500 employees divided by the number of employees (thousands) in large firms. Similarly, the innovation rate for small firms is defined as the number of innovations made by firms with fewer than 500 employees divided by the number of employees (thousands) in small firms.

Innovation rates, or the number of innovations per thousand employees, have the advantage that they measure innovative activity in large and small firms relative to the presence of large and small firms in any given industry. Thus, for example, while large firms in manufacturing introduced 2445 innovations and small firms contributed slightly fewer (1954), employment in small firms was only half that in large firms, yielding an average innovation rate in manufacturing of 0.309 for small firms compared with an average innovation rate of 0.202 for large firms (Acs and Audretsch, 1988, 1990).

What explains this innovation paradox, where small and new firms are empirically found to generate more innovative activity than would be expected given their meagre R&D resources? Resolution of this paradox lies again in considering both the nature of knowledge within the context of the organizations creating that knowledge and the role of entrepreneurship, or what Audretsch et al. (2006) term the knowledge spillover theory of entrepreneurship.

Because of the conditions inherent in radical innovation based on knowledge — high uncertainty, asymmetries and transactions cost — decision-making hierarchies can reach the decision not to commercialize new ideas that individual economic agents, or groups of economic agents, think are potentially valuable and should be pursued. The characteristics of knowledge that distinguish it from information — a high degree of uncertainty combined with non-trivial asymmetries, combined with a broad spectrum of institutions, rules and regulations — distinguish radical innovation from incremental innovation.

Thus, not all potential innovative activity, especially radical innovations created through scientific discoveries and inventions, is fully appropriated within the firm making investments to create that knowledge in the first place. Various constraints on the ability of a large firm to determine the value of knowledge prevent it from fully exploiting the inherent value of its knowledge assets (Moran and Ghoshal, 1999). In fact, evidence suggests that many large, established companies find it difficult to take advantage of all the opportunities emanating from their investment in scientific knowledge (Christensen and Overdorf, 2000). For example, Xerox's Palo Alto research centre succeeded in generating a large number of scientific breakthroughs (a superior personal computer, the facsimile machine, the Ethernet and the laser printer, among others), yet failed to commercialize many of them and develop them into innovations (Smith and Alexander, 1988; Chesbrough and Rosenbloom, 2002).

The knowledge conditions inherent in radical innovation impose what Audretsch et al. (2006) and Acs et al. (2004) term *the knowledge filter*. The knowledge filter is the gap between knowledge that has potential commercial value and knowledge that is actually commercialized in the form of innovative activity. The greater the knowledge filter, the more pronounced the gap between new knowledge and commercialized knowledge in the form of innovative activity.

An example of the knowledge filter confronting a large firm is provided by the response of IBM to Bill Gates, who approached IBM to see if it was interested in purchasing the then struggling Microsoft. They weren't interested. IBM turned down, "the chance to buy ten percent of Microsoft for a song in 1986, a missed opportunity that would cost $3 billion today."[3] IBM reached its decision on the grounds that "neither Gates nor any of his band of thirty some employees had anything approaching the credentials or personal characteristics required to work at IBM."[4]

Thus, the knowledge filter serves as a barrier impeding investments in new knowledge from being pursued and developed to generate innovative activity. In some cases, a firm will decide against developing and commercializing new ideas emanating from its knowledge investments even if an employee, or group of employees, think they have a positive expected value. As explained above, this divergence arises because of the inherent conditions of uncertainty, asymmetries and high transactions costs which create the knowledge filter.

While Griliches' model of the knowledge production function focuses on the decision-making context of the firm concerning investments in new knowledge,

[3] "System Error," *The Economist*, September 18, 1993, p. 99.
[4] Paul Carrol, "Die Offene Schlacht," *Die Zeit*, No. 39, September 1993, p.18.

Audretsch (1995) proposed shifting the unit of analysis from the firm to the individual knowledge worker (or group of knowledge workers). This shifted the fundamental decision-making unit of observation in the model of the knowledge production function away from exogenously assumed firms to individuals, such as scientists, engineers or other knowledge workers — agents with endowments of new economic knowledge. Shifting the focus away from the firm to the individual as the relevant unit of observation also shifts the appropriation problem to the individual, so that the relevant question becomes how economic agents with a given endowment of new knowledge can best appropriate the returns from that knowledge. If an employee can pursue a new idea within the context of the organizational structure of the incumbent firm, there is no reason to leave the firm. If, on the other hand, employees place greater value on their ideas than the decision-making hierarchy of the incumbent firm, they may face forgoing what has been determined to be a good idea. Such divergences in the valuation of new ideas force workers to choose between forgoing ideas or starting a new firm to appropriate the value of their knowledge.

By focusing on the decision-making context confronting the individual, the knowledge production function is actually reversed. Knowledge becomes exogenous and embodied in a worker. The firm is created endogenously in the workers' efforts to appropriate the value of their knowledge through innovative activity. Typically, an employee in an incumbent large corporation, often a scientist or engineer working in a research laboratory, will have an idea for an invention and ultimately for an innovation. Accompanying this potential innovation is an expected net return from the new product. The inventor would expect compensation for the potential innovation accordingly. If the company has a different, presumably lower, valuation of the potential innovation, it may decide either not to pursue its development or that it merits a lower level of compensation than that expected by the employee.

In either case, employees will weigh the alternative of starting their own firm. If the gap in the expected return accruing from the potential innovation between the inventor and the corporate decision maker is sufficiently large, and if the cost of starting a new firm is sufficiently low, the employee may decide to leave the large corporation and establish a new enterprise. Since the knowledge was generated in the established corporation, the new start-up is considered to be a spinoff from the existing firm. Such start-ups typically do not have direct access to a large R&D laboratory. Rather, the entrepreneurial opportunity emanates from the knowledge and experience accrued from the R&D laboratories of the previous employer. Thus, entrepreneurship is an endogenous response to opportunities created by investments in new knowledge that are not commercialized because of the knowledge filter. By resorting to starting up a new firm to actualize the commercialization of ideas that otherwise might remain dormant in the incumbent firm, entrepreneurship serves as a conduit for knowledge spillovers.

Knowledge created in one organizational context that remains uncommercialized due to the knowledge filter provides an important source of new entrepreneurial opportunities. It is new knowledge and ideas created in one context but left uncommercialized or not vigorously pursued by the organization actually creating those ideas, such as a research laboratory in a large corporation or research undertaken by a university, that serves as the source of knowledge generating entrepreneurial opportunities. Thus, entrepreneurship can serve as an important mechanism facilitating the spillover of knowledge. The incumbent organization creating the knowledge and opportunities is not the same firm that actually exploits the opportunities. If the exploitation of those opportunities by the entrepreneur does not involve full payment to the firm for producing those opportunities, such as a licence or royalty, then the entrepreneurial act of starting a new firm serves as a mechanism for knowledge spillovers.

Thus, new knowledge generating opportunities for entrepreneurship is the duality of the knowledge filter. The higher the knowledge filter, the greater the divergence in the valuation of new ideas between economic agents and the decision-making hierarchies of incumbent firms. Entrepreneurial opportunities are generated not just by investments in new knowledge and ideas, but by the propensity for only a distinct subset of those knowledge opportunities to be fully pursued and commercialized by incumbent firms. Thus, entrepreneurship is important in generating innovative activity in general and radical innovations in particular by serving as an important conduit of knowledge spillovers.

4. Measuring and Defining Radical Innovation

4.1 Expert Panels

There is a long tradition of relying on industry experts to identify innovative activity. The first serious attempt to directly measure innovative output was made by a panel of industry experts assembled by the Gellman Research Associates (1976) for the National Science Foundation. The Gellman panel identified 500 major innovations that were introduced into the market between 1953 and 1973 in the United States, the United Kingdom, Japan, West Germany, France and Canada. The database was compiled by an international panel of experts who identified those innovations representing the “most significant new industrial products and processes, in terms of their technological importance and economic and social impact” (National Science Board, 1975, p. 100).

A second and comparable database once again involved an expert panel assembled by the Gellman Research Associates (1982), this time for the U.S. Small Business Administration. In their second study, the Gellman panel identified 635 U.S. innovations, including 45 from the earlier study for the National Science Foundation. The remaining 590 innovations were selected from 14 industry trade journals for the period 1970–1979. About 43 percent of the sample was selected from award-winning innovations described in *Industrial Research and Development* magazine.

A third data source to directly measure innovation activity was compiled at the Science Policy Research Unit (SPRU) of the University of Sussex in the United Kingdom.[5] The SPRU data consist of a survey of 4378 innovations that were identified over a period of 15 years. The survey was compiled by writing to experts in each industry and requesting them to identify "significant technical innovations that had been successfully commercialized in the United Kingdom since 1945, and to name the firm responsible" (Pavitt et al., 1987, p. 299).

Another study conducted by Acs and Audretsch (1990) looked at 4938 innovations and their levels of significance (Table 4): (1) the innovation established an entirely new category of product, (2) the innovation is the first of its type on the market in a product category already in existence, (3) the innovation represents a significant improvement in technology, and (4) the innovation is a modest improvement designed to update an existing product (Acs and Audretsch, 1990).

Table 4 Distribution of Innovations of Large and Small Firms According to their Level of Significance (percentages in parentheses)

Level of Significance	**Description**	**Number of Innovations**				
		Large Firms			**Small Firms**	
1	Established a new product category	(0.00)	(0.00)		(0.00)	(0.00)
2	First of its type on the market in an existing product category	50	(1.76)		30	(1.43)
3	Significant improvement in existing technology	360	(12.70)		216	(10.27)
4	Modest improvement designed to update an existing	2434	(85.53)		1959	(88.31)

[5] The SPRU innovation data are explained in detail in Pavitt et al. (1987), Townsend et al. (1981), Robson and Townsend (1984) and Rothwell (1989).

	product					
Total		2834	(99.99)		2104	(100)

Source: Audretsch and Acs (1990)

Acs and Audretsch (1990) found that while none of the innovations were at the highest level of significance, they did find that small firms make up a considerable portion of the innovations within the field. There appears to be little difference in the "quality" and significance of innovations between large and small firms.

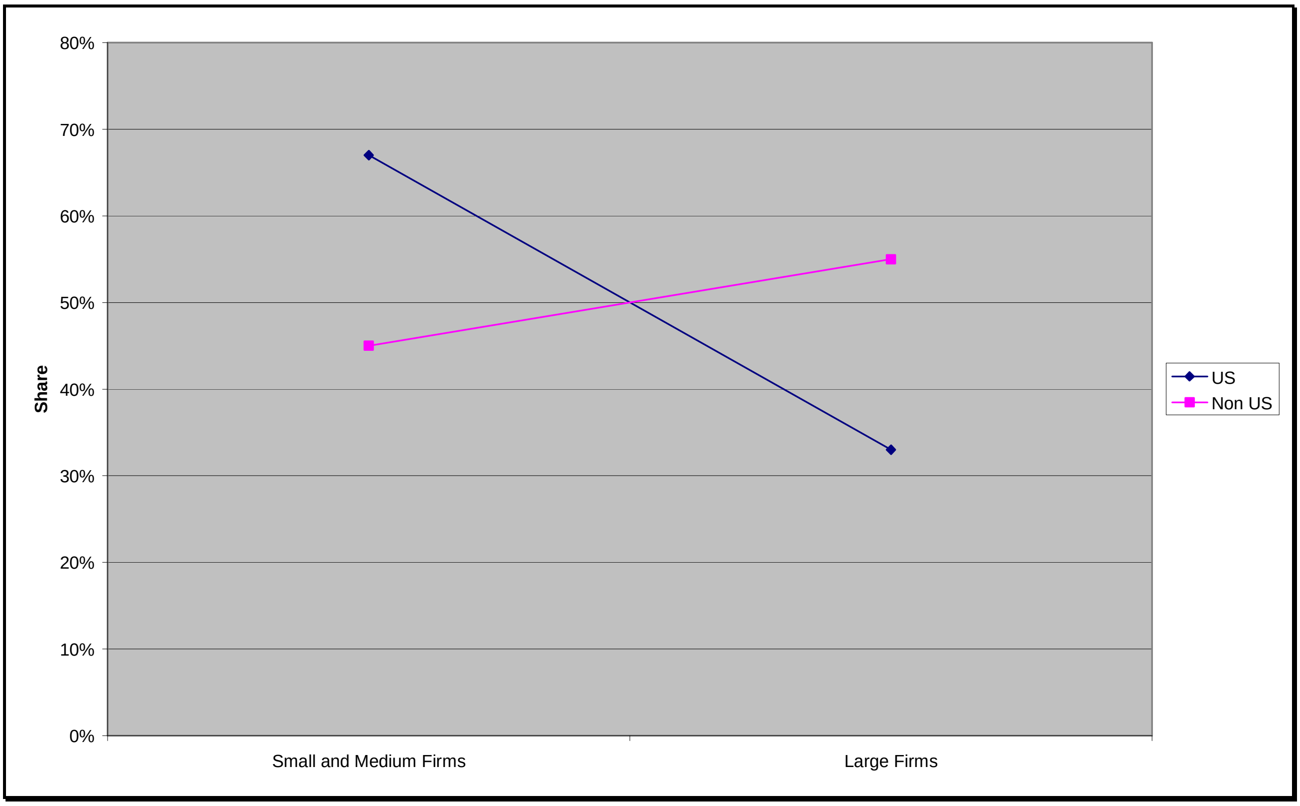
The most recent and ambitious major database providing a direct measure of innovative activity is the U.S. Small Business Administration's Innovation Data Base (SBIDB). The database consists of 8074 innovations commercially introduced in the U.S. in 1982. A private firm, The Futures Group, compiled the data and performed quality-control analyses for the U.S. Small Business Administration by examining more than 100 technology, engineering and trade journals spanning every industry in manufacturing. Industry experts were relied upon to identify innovations as well as their significance. From the sections in each trade journal listing innovations and new products, a database consisting of innovations by four-digit standard industrial classification (SIC) industries was established. Many of the innovations were classified according to four distinct levels of significance, ranging from incremental, which referred to quality improvement, to most significant, which presumably referred to a radical innovation.[6]

Dewar and Dutton similarly relied upon an *ex post* study of experts to identify specific radical innovations and suggest that, "the major difference captured by the labels radical and incremental is the degree of novel technical process content embodied in the innovation and hence, the degree of new knowledge embedded in the innovation" (Dewar and Dutton, 1986, p. 1429). This distinction is consistent with those researchers who define technology in terms of its knowledge component (Dutton and Thomas, 1985). Although radical and incremental pertain to distinctions along a theoretical continuum of the level of new knowledge embedded in an innovation, the middle values of this continuum are difficult to interpret (Baumol 2004).

Another expert panel study found that there are large discrepancies between innovations by small and large firms among U.S. and non-U.S. companies. As shown by Chandy and Tellis (2000) in Figure 1, only 45 percent of non-U.S. small firms created radical innovations, while 66 percent of U.S. small firms created radical innovations.

[6] A detailed description of the U.S. Small Business Administration's Innovation Data Base can be found in Chapter 2 of Acs and Audretsch (1990).

Figure 1 Share of Radical Innovations by Firm Size and Country for Consumer Durables and Office Products

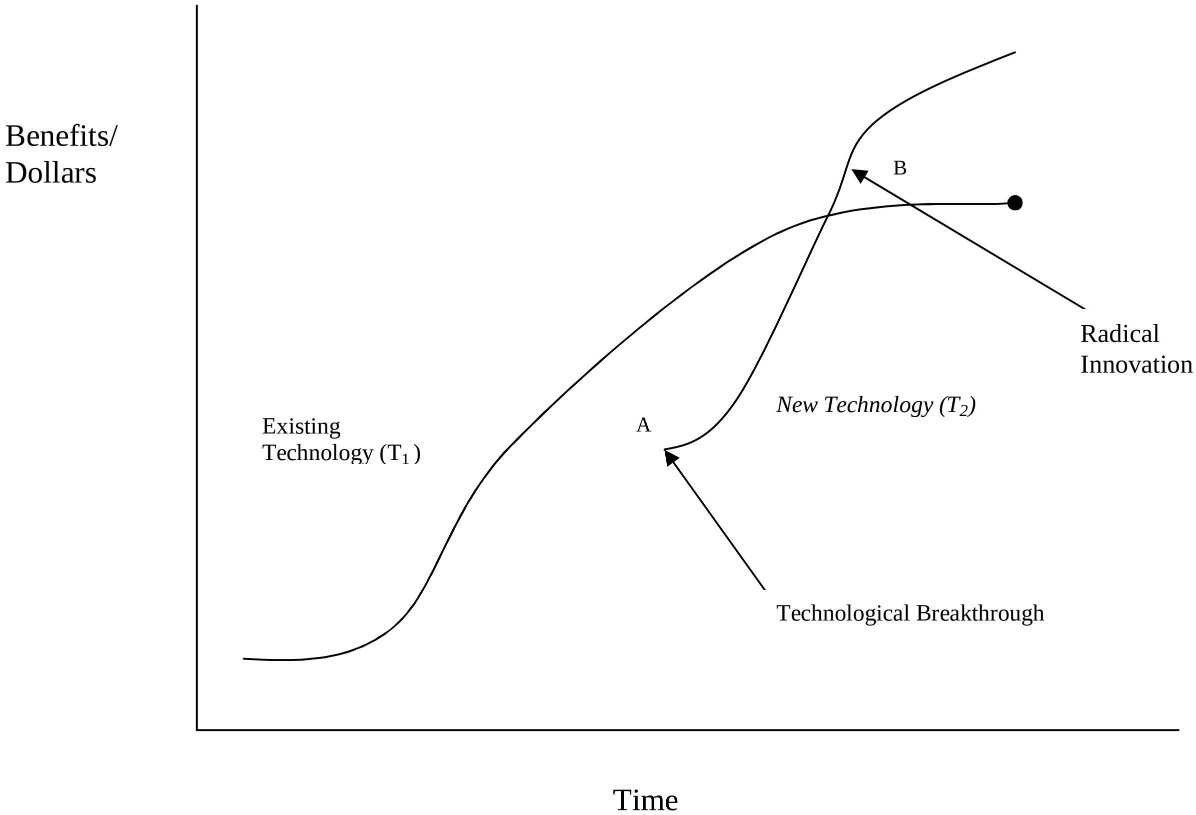


Source: Chandy and Tellis (2000)

4.2 S-Curves and Technological Trajectories

Dosi (1982) enters the theoretical discussion by describing how discontinuous and continuous technological trajectories can be distinguished. Much of the foundation for this area of research uses Schumpeterian economic evolution to understand the innovation process. In particular, Dosi develops a framework for distinguishing radical innovation from incremental innovation based on the technological push and consumer demand for innovation. Dosi suggests that an incremental innovation extends an existing technological paradigm. By contrast, a radical innovation creates a new technological paradigm. According to Dosi (1982, p. 150), “Technological paradigms have a powerful *exclusion effect*: the efforts and the technological imagination of engineers and the organizations they are in are focuses in rather precise direction while they are, so to speak, ‘blind’ with respect to other technological possibilities. At the same time, technological paradigms define also some idea of ‘progress’.” As shown in Figure 2, there are two points of innovation.

Figure 2 S-Curve of Radical Innovation



Source: Chandy and Tellis (2000, p. 3)

At point A, there is a technological breakthrough. This breakthrough allows the firm to properly estimate how and when it may introduce the innovation to the market. This new technology over time succeeds the existing technology. Once the technological breakthrough enters (point B) into the existing technological curve, it provides greater value added and supersedes the existing technology.

As Dahlin and Bohrens (2004) rightly point out: "A related approach suggests that the development of technologies subsequent to the introduction of a radical innovation will follow the path of an S-curve. However, as is the case for technological trajectories, S-curves do not offer a precise manner for mapping technologies. Neither do they help us identify, or define, the radical invention that will start a new S-curve. In effect, whereas one needs to have good ideas about what the important performance criteria are a priori, such ideas appear to us only a fortiori in Dosi and Foster's framework analyzing radical innovations."

4.3 Hedonic Price Models

This strand of literature stems from Henderson and Clark (1990) and Henderson (1993), where price is the empirical measure used to determine radical innovation. Henderson studies the lithographic industry. While hedonic pricing traditionally limits itself to technological fields, it provides a quantifiable means to understand the impact of variables on price. For example, instead of just comparing the price of a black-box camera with a digital camera, the model would adjust for incremental improvements in the process, such as a flash or quicker shutter speed. Therefore, it provides a simple way to understand how supplementary additions in the quality of a product affect price. Henderson (1993, p. 258) finds that "prior experience is significantly and negatively correlated with realized market share for radical innovation, providing strong support for the hypothesis that incumbents attempting to introduce products that require quite different organizational capabilities were severely handicapped."

There are multiple problems with this method. The most crucial problem is that the method is unable to test for new fields that are dormant or in an emerging field. Indeed, 15 years prior to her study, the radical innovation of the digital camera was already owned and operated by the Kodak Eastman Company.[7] Other problems with the method, for example, are that the hedonic price index approach incorporates the productivity of individuals, and multiple product levels can be tested. However, one must pre-select what product characteristics might predict the degree to which an innovation is radical. Another problem is that the willingness to pay may be more likely with incremental changes (Tellis and Golder, 1996; Shane, 2001).

4.4 Codified Innovation: Patents

Over the past 20 years, patents have become one of the most common means of measuring the degree to which an innovation is radical or incremental. Patents have become an important metric in the innovation literature because of an easy and open paper trail of patent citations. This trail leaves a clearly defined origin of ideas and represents a clear lineage of where ideas go when they are cited in the future. This lineage comes in two forms: forward citations and backward citations. Patent citations also indicate a clear economic value to start-ups and economic growth (Trajtenberg, 1990). Since patent citations are equitable to a patent monopoly, there are strict procedures to ensure that appropriate citations are issued, creating a platform for researchers to apply empirical investigation for radical innovation.

4.4.1 Forward Patent Citation Radicalness

Forward patent citation involves future citations of a patent. These citations come from United States patent examiners. These professionals cite the previous patent only when there is a legitimate reason to cite the previous patent's intellectual property. These future citations are called forward patent citations. Rosenkopf and Nerkar (2001) measure the degree of radicalness by examining the computer disk industry to investigate the impact patents have on future citations in domains of patent classification. Patent domains are maintained and categorized by the United States Patent and Trademark Office (USPTO). The authors' show how incremental patents are often more narrowly cited within a certain domain of patents and radical patents are often cited by multiple domains of patents.

The forward patent count that Rosenkopf and Nerkar (2001) use is, in many ways, comparable to forward citations in scholarly journals. There are, however, two detrimental differences when using citations. First, there is a motivation from the patent inventor to cite as little as possible from previous work. The less work that is cited in the grant application, the more intellectual property (IP) monopoly is granted to the inventor. Second, a patent examiner is required to assign relevant patent citations to the patent application. For a greater understanding of deficiencies in the U.S. patent-examining process, see Graham and Harhoff (2006) and Harhoff et al. (2002). Drawing on patent citations creates other problems as well. As Rosenberg and Nekar (2001, p. 290) define radical innovation: "'radical' exploration builds upon distant technology that resides outside of the firm. The technological subunit utilizes knowledge from a different technological domain and does not obtain that knowledge from other subunits with the firm."

The definition of radicalness holds innovation exogenous to the human capital and tacit knowledge of the firm. As Klepper and Graddy (1990) suggest, new and radical innovations can come from subunits within the firm. The distant technology can often be found within the incumbent firm. However, the firm is unwilling to either operationalize the potential radical innovation due to managerial disagreements or commit resources to a new and uncertain venture.

4.4.2 Backward Patent Classification and Citations

Backward patent citations are citations given to prior work. These citations are issued by patent examiners where examiners cite previous patents, thereby giving the citations a clear line of intellectual property rights. Shane (2001) shows, through a unique data set from Massachusetts Institute of Technology (MIT) inventors involving 1397 licensed MIT patents, that the more radical the invention, the more likely it was made by a small firm. As Shane (2001, p. 208) explains, radical innovations will tend to originate from small firms and large firms: "First, radical technologies destroy the capabilities of existing firms because they draw on new technical skills. Since organizational capabilities are difficult and costly to create (Nelson and Winter, 1982; Hannan and Feeman, 1984), established firms are organized to exploit established technologies. Firms find it difficult to change their activities to exploit technologies based on different technical skills." Shane (2001) finds that research suggests that radical patent citations and a lack of patent classification are positive to start-ups for the MIT-based patents. As one may note from Table 5, Shane's method of radical identification is one of many ways to identify radical innovations.

Table 5 Literature Summary of Radical Innovations

Commonly used definitions of radical versus incremental changes		
Studies in chronological order	**Industries studied**	**Definition of novelty**
Cooper and Schendel (1976)	Locomotives, fountain pens, vacuum tubes, fossil fuel boilers, safety razors, propellers, leather	None. Selected industries in which almost full substitution occurred when innovation was introduced
Dosi (1982)	Theory paper	Technological paradigm = "model" and a "pattern" of solution of selected technological problems, based on selected principles derived from natural sciences and on selected material technologies (p. 152); radical change; paradigm shift
Foster (1985)	Multiple examples, e.g., watches, artificial hearts, textile fibres, semiconductors	Discontinuity = gap between two S-curves at a point where one technology replaces another
Dewar and Dutton (1986)	Shoe manufacturing	Radical innovations require adopting firm to process new information
Anderson and Tushman (1990)	Glass, cement and minicomputers	Two dimensions: (1) order-of-magnitude change in price-performance ratio; (2) competence-enhancing versus competence-destroying
Henderson and Clark (1990)	Theory paper	Two dimensions: (1) design architecture is reinforced or changed; (2) core technological concepts in componentry are reinforced or changed
Henderson (1993)	Photolithographic alignment equipment	Two dimensions: (1) degree of substitutability; (2) competence-enhancing versus competence-destroying
Das (1994)	Theory paper	Two dimensions: (1) knowledge same or different; (2) competence-enhancing versus competence-destroying

Christensen and Rosenbloom (1995)	Disk drives	Radical = launching new direction in technology versus Incremental = making progress along established path
Christensen and Bower (1996)	Disk drives	Radical = disrupts or redefines a performance trajectory Incremental = sustains the industry's rate of improvement in product performance
Tripsas (1997)	Graphical typesetting	None
Chandy and Tellis (2000)	Consumer durables and office products	"a new product that incorporates a substantially different core technology and provides substantially higher customer benefits relative to previous products in the industry" (p. 2)
Rosenkopf and Nerkar (2001)	Optical disk technology	"Radical exploration builds upon distant technology that resides outside of the firm." (p. 290)
Shane (2001)	MIT-licensed patents	"I measure the radicalness of the patent as a time-invariant count of the number of three-digit patent classes in which *previous* patents cited by the given patent are found, but the patent is not classified" (p. 210)
Ahuja and Lampert (2001)	Chemicals	Radical/breakthrough inventions "serve as the basis of 'future' technologies, products and services." (p. 522)
Dahlin and Behrens (2005)	Tennis racquets	Three criteria: (1) the invention must be novel: it needs to be dissimilar from prior inventions; (2) the invention must be unique: it needs to be dissimilar from current inventions; (3) the invention must be adopted: it needs to influence the content of future inventions

Adapted from Dahlin and Behrens (2005)

4.5 Dahlin and Behrens Metric for Radical Innovations

As one can see, radical innovations come in multiple paths and trajectories. Whether through small or large firms, these innovations are able to transform the nature of the market to the advantage of the radically innovative firm. The best method to identify an *ex ante* radical innovation, therefore, is through the only available paper trail of patents. As mentioned earlier, analysis has used either forward patent or backward patent citations, but has never used both to dynamically analyze the data. Dahlin and Behrens (2005) use patents from the tennis racquet industry to show that there is not only a way to *ex ante* identify whether an invention is radical, but also a way to systematically analyze a product market to determine whether the innovation is radical.

Dahlin and Behrens offer an attractive means to identify incipient radical innovations a priori, or before they are actually fully developed and introduced. They create a three-stage metric process that distinguishes between radical invention and radical innovation. This is an important process. As mentioned in previous sections, other methods were unable to identify radical inventions and therefore the potential radical innovation in the pipeline. As mentioned above, for example, innovations from large firms, such as the Kodak digital camera, were not recognized as radical inventions due to a lack of proper identification metrics. This method offers a needed predictive power of identifying patents that have the potential to be radical innovations. The model offers three criteria and is based on the structure of patent citations and replication of new patent citations.

The Dahlin and Behrens model identifies radical inventions as inventions that heavily influence and affect the future content of patent families. Therefore, the patent must be unique to other patents in terms of its patent structure and future citations. This uniqueness is identified by the criteria presented in Table 5.

Dahlin and Behrens' model places emphasis on how dissimilar the patent is to past and current inventions. Therefore, when new patents are filed, the new patents' citations are compared with the identified radical invention. If the new patents replicate a similar patent structure to the identified radical patent, the radical patent is then classified as a radical innovation. In Table 6, the advantages of using the Dahlin-Behrens model are examined.

Table 6 Characterizing Each Definitional Form of Radical Innovation

	S-Curves	**Hedonic Price Models**	**Expert Panels**	**Patent Measures**	**Dahlin-Berhens**
Practical problems					
1. Lacks quantifiable measurement indicating when an invention is radical	Yes — need expert help to determine if a new trajectory/curve is started	Yes — focuses on price increases as a function of technical criteria, but any price increase counts	No — uses scales of expert perceptions	No — but cut-off points often arbitrary and not defined a priori	No — uses patent citations
2. Difficulty of timing — when to compare innovations	No — assumes multiple time comparisons	No — allows for multiple time comparisons	Yes — focuses on experts at one point in time	Yes — for forward citations; no — for backward citations	No — analyzes both past and currentinnovation structure
3. Difficulty in accessing data	Difficult	Medium difficulty	Easy	Easy	No — data are freely accessible
4. A priori key characteristic determined?	Yes — model is predefined as effort and technical impact	No — models are variable	No — varies from expert to expert	Yes — patent citations	Yes — patent citations
Conceptual problems					
1. Performance-comparison issues	Allows for continuous comparisons over time since multiple trajectories/curves	Medium, easy to test multiple criteria simultaneously	Depends on questionnaire	Yes — for forward citations, mainly timing issues	No — one may track the performance of the citations
2. Impact-based definition	No	Yes — if no effect on demand (price higher), not considered radical	Standard questions have impact bias, could be removed	Yes — for forward citations; no — for backward citations	No — impact is based on citations and noton actual commercial output
3. Assumptions of firm homogeneity	No	No — focus on product characteristics	Standard questions have impact bias, could be removed	Yes — for forward citations, ignoring the likelihood ofbeing cited is afunction of firm status; no — for backwardscitations	Yes — for forward citations, ignoring the likelihood of being cited is a function of firm status; no — for backwards citations
4. Selection bias	Depends on data source and how trajectories/curves are identified	Yes — only characteristics in products with market success will be included	Yes — recency and success biases also likely	No	No

5. Conclusion

In this paper, we offer a literature review of how radical innovation is quantified and the metrics applied for identifying radical innovation. As suggested in the literature, there are conflicting empirical metrics identifying radical innovation. Consequently, there is conflicting empirical evidence on the propensity for small and large firms to engage in radical innovation. After all, according to the literature, it surely cannot be that both large firms are “incompetent” and small firms are “inferior” with respect to radical innovations. These empirical inconsistencies lie, to some degree, in how one identifies a radical invention.

While not perfect, the Dahlin-Behrens model provides policy-makers with an easily accessible and identifiable means to properly identify radical innovations *ex ante*. This identification requires that the radical innovation 1) be dissimilar to previous patent citations, 2) differ from existing patent citations, and 3) affect future patent citation structures. The three-stage definition offers explicit advantages over previous identification regimes. Specifically, technical content is identified and tracked over time. The definition also eliminates many of the problems found in other identification metrics, such as 1) definition and measurement, 2) ability to identify an invention that is still in the development phase, and 3) identification is not measured by *ex post* analysis.

While it will continue to be unclear what share of radical innovation originates from small and large firms, the ability to identify the invention will be the critical aspect for policy-makers and then to identify whether the invention is from a large or small firm. Therefore, the authors believe that radical innovation should not necessarily be analyzed under the large or small firm unit of analysis, but rather radical innovations should be identified and tracked within and coming out of the pipeline.

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