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# When is an invention really radical? Defining and measuring technological radicalness

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**Abstract**

We develop a valid definition of technological radicalness which states that a successful radical invention is: (1) novel; (2) unique; and (3) has an impact on future technology. The first two criteria allow us to identify potentially radical inventions ex ante market introduction; adding the third condition, we can ex post determine if an invention served as an important change agent. Empirically testable condition selected 6 of 581 tennis racket patents granted between 1971 and 2001. Two of the identified patents – the oversized and the wide-body rackets – are considered radical inventions by industry experts. Applying our definition and operationalization would allow researchers to achieve greater generalizability across studies, avoid endogenous definitions of radicalness, and study predictors of market success for radical inventions.


*Keywords:* Radical innovation; Operationalization and measurement; Patent citations

When is an invention radical? Many studies distinguish between run-of-the-mill inventions, often labeled incremental, and those inventions that break with traditions in a field, often labeled radical, discontinuous, generational, or breakthrough (Anderson and Tushman, 1990; Christensen and Rosenbloom, 1995; Cooper and Schendel, 1976; Tripsas, 1997). Few studies, however, clearly define the difference between these two categories. And still fewer studies, in addition to lacking definitions, measure the difference between radical and incremental inventions; they offer little guidance regarding ways of identifying and validating if, and when, an invention is radical. This paper provides a valid definition as well as a set of empirically testable conditions to identify and measure radicalness in inventions. A clear and reproducible definition and measure of radicalness will improve generalizability across studies and help to build a cumulative body of work dealing with radical technological change.[1]

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[1] We will use the convention of labeling a new idea or product an *invention* if its market success is unknown; we use the label *innova-*


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In this paper, we define the term *radical invention* and develop a measure of radicalness. We begin by asking, in Section 1, just what a radical invention is. In Section 2, we discuss in some detail the definitions and measures from prior research and end with three defining conditions. In Section 3, we outline how to operationalize the proposed definition using patent citation data. We then test the operationalization on a data set of 581 patents in the tennis racquet industry and compare the radical inventions identified by our method with those already identified by industry experts as radical; we also compare the method with using direct citation counts concluding that our method is better at finding radical inventions and has less of a time bias. Finally, in Section 4, we discuss the results and conclude with implications and suggestions for future research.

## 1. Background

Interest in radical innovation originated with Schumpeter (1934), one of the first to claim that radical technological change is a powerful mechanism that can challenge the power of monopolists. Schumpeter's main argument was that the nature of radical technological change undermines the very foundation of large firms' competitive advantages – cost leadership due to large production volumes in an established technology – by rendering the established technology irrelevant. That innovation might really have such a profound effect on competition and firm survival has intrigued economists, organizational and strategic scholars, as well as policy makers. Many empirical studies have tested Schumpeter's ideas (cf. Anderson and Tushman, 1990; Henderson, 1993; Cooper and Schendel, 1976; Tripsas, 1997; King and Tucci, 2002). In fact, Schumpeter's arguments were considered important enough to be brought up in the US government's anti-trust law suit against Microsoft Corporation (Evans and Schmalensee, 2000), where the defending side cited Schumpeter and argued that a near-monopolist like Microsoft only holds a temporary market position since a new radical innovation will upset the status quo sooner or later.

*tion* when there is established commercialisation; and finally, we use the label *radical technological change* when a radical invention has been successful in converting an industry.

Despite a growing acceptance of and interest in the theory, there is one clear shortcoming: studies define radical technological change differently (if at all) and, consequently, the measurement of such changes vary greatly. But generating a stable definition and a consistent operationalization is necessary if we are to compare and contrast findings and better understand the role of radical change in restructuring industries. In addition to variations in definitions and measurements of radical technological change, prior work has used retrospective measures to identify radical innovations. It would be far more useful to identify radical inventions at the time, or even before, they enter the market, since it would help solve a selection bias that plagues most studies. Past studies using retrospective measures are typically only able to identify new technologies after they have succeeded commercially. But 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 (such as market power of the supplier).[2] Ideally, we should not confuse the definition of radical technological change with such conditions. Early detection of inventions with the potential to start a radical change in an industry might also be useful for managers and policy makers, since they could then evaluate the technology and plan a response at an earlier stage.

In this paper we propose three conditions for what makes an invention radical, allowing for ex ante identification of potential radical invention and ex post evaluation of its impact. We focus the definition of radicalness on an invention's technical content, thus avoiding the drawbacks of many commonly used definitions that often confound radicalness with its impact on an industry. Our aim is to create an easy-to-use and consistent method to identify and assess radicalness in inventions across technological fields. Finally, our definition and measures allow us to distinguish between successful and unsuccessful radical inventions, thereby avoiding the problem of a

[2] Both Shane (2001) and Åstebro and Dahlin (2005) find that the more radical an invention the less likely it is to be commercialized.

Table 1
Commonly used definitions of radical vs. 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 techology 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 | 2 dimensions: (1) order-of-magnitude change in price-performance ratio; (2) competence-enhancing vs. competence -destroying |
| Henderson and Clark (1990) | Theory paper | 2 dimensions: (1) design architecture is reinforced or changed; (2) core technological concepts in componentry are reinforced or changed |
| Henderson (1993) | Photolithographic alignment equipment | 2 dimensions: (1) degree of substitutability; (2) competence-enhancing vs. competence -destroying |
| Das (1994) | Theory paper | 2 dimensions: (1) knowledge same or different; (2) Competence-enhancing vs. competence -destroying |
| Christensen and Rosenbloom (1995) | Disk drives | Radical = launching new direction in technology vs. 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 |
| Rosenkopf and Nerkar (2001) | Optical disk technology | "Radical exploration builds upon distant technology that resides outside of the firm." (p. 290) |
| Ahuja and Lampert (2001) | Chemicals | Radical/breakthrough inventions "serve as the basis of 'future' technologies, products and services." (p. 522) |

success bias and making possible the study of what makes a radical technological invention successful.

### *1.1. Current schools of thought—strengths and shortcomings*

Some studies concerned with radical change avoid defining the construct (for critiques see Acs et al., 2002; Das, 1994; Ehrnberg, 1995; Silverberg, 2002). Moreover, when studies do include a definition (see Table 1) these definitions are often vague and vary from those used in previous studies. In this section, we discuss: (1) definitions of radical invention used in the literature; and (2) measures and methods following those definitions. We end with a summary critique of the problems with these definitions and measures and suggest a solution.

The most general models and methods used to describe and measure radicalness of innovation are the following: (1) technology cycles (Anderson and Tushman, 1990); (2) s-curves (Foster, 1985) and technological trajectories (Dosi, 1982; Christensen and Rosenbloom, 1995); (3) hedonic price models (Henderson, 1993); and (4) expert panels (Dewar and Dutton, 1986). As well, a series of more specific measures has been developed using patent data.

#### *1.1.1. Technology cycles*

In a series of papers, Tushman and Anderson (1986), Anderson and Tushman (1990) develop Utterback and Abernathy's (1975) ideas about technology cycles, using rate of performance improvements to identify radical inventions. Tushman and Anderson study performance improvements over time on a single important performance dimension. When a large increase in the state-of-the-art performance is detected, it is deemed to have been caused by a radical innovation if the performance spike can be connected in time to a known invention. An attractive feature of this method is that it explicitly examines the technical performance of technologies and quantifies changes in performance due to innovation.

A more problematic issue of applying this method is its focus on a single performance dimension when, in fact, radical inventions often refocus attention on a new performance dimension (White, 1978; Dosi, 1982). Thus a single performance dimension is rarely sufficient to describe and capture the evolution of a particular product technology. Since a breakthrough innovation usually underperforms vis-à-vis an established technology for a period of time before it catches up and, potentially, surpasses the old technology (Christensen and Rosenbloom, 1995), it is not clear that Tushman and Andersons' criterion of a contemporaneous large increase in performance will allow for the identification of many radical inventions. In all likelihood, the necessity to observe a drastic increase in a technology performance index with the introduction of an invention only leads to a large under-reporting of radical inventions. Practically speaking, whereas the conceptual impact of Tushman and Anderson's ideas can hardly be overstated, actually applying the method seems difficult. Indeed, we have found no empirical papers beyond those by Tushman and Anderson that use the method.

#### *1.1.2. Technological trajectories and s-curves*

Technological trajectories and s-curves are two related methods that track products' technical performance over time or per engineering hour (Dosi, 1982; Foster, 1985). Both these methods differ from Tushman and Anderson's model inasmuch as they compare multiple technologies' performance over time, often on more than one performance criteria. Performance comparisons between technological trajectories are frequently made in graph form to illustrate how relative performance advantages between competing technologies shift over time. Each trajectory indicates a path of incremental inventions. The start of a new trajectory would then indicate a radical invention.

Similar to Dosi's (1982) trajectories, Foster's (1985) s-curves are used to trace competing technical solutions along separate performance curves. The s-shape of the curves represents an empirical regularity in how technologies typically progress. Explicitly separating competing technical solutions by allocating them different curves in the same graph will indicate when one technology outperforms another and if a discontinuity is likely to occur. As occurs with Dosi's trajectories, s-curves do not offer a way of identifying what technologies to map. Neither do they help us identify, or define, the radical invention that will start a new curve. In effect, whereas we need 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 world.

Extrapolating from the trajectories theory, Christensen and colleagues define a radical change as an invention that "launches a new direction in the technology" (Christensen and Rosenbloom, 1995) and as an invention that "disrupts or redefines a performance trajectory" (Christensen and Bower, 1996). There is, unfortunately, no direct measure of what makes one invention radical and another incremental. Identification of radical changes is made after the fact and with little systematic analysis of exogenous data or criteria; thus, while the theories are broad and rich in description, neither trajectories nor s-curves really help us to identify radical innovations.

#### *1.1.3. Hedonic price models*

Hedonic price models are regression models that use price as a dependent variable and product characteristics as independent, or predictor, variables. An invention is confirmed to be radical if the predictor variables measuring the content of the potentially radical invention are found to be statistically significant (Henderson, 1993; Tirole, 1988). Thus an invention is considered radical if the market is willing to pay a higher price for it. This approach has several strengths: multiple product characteristics can be tested simultaneously and their relative importance compared, and the simple treatment of the technology variables (dummies indicating presence in a product) makes this approach straightforward to use. Weaknesses of the method include sensitivity to model specification (the fewer the product characteristics, the more likely one is to get significant results for the ones included); the need to pre-specify what product characteristics might predict radicalness; and the use of the market's willingness to pay a higher price for the improvement as a proxy for technological improvement. Market willingness to pay is a problematic definition and measure of radicalness; indeed, small incremental changes might be generating a more immediate economic pay-off than radical changes (Shane, 2001; Tellis and Golder, 1996). A limitation of this approach is its dependence on historical market data and its uselessness as a forecasting tool. In summary, hedonic models indicate the impact of product features on market value.

*1.1.4. Expert panels*

Expert panels are used to evaluate a set of inventions on scales usually capturing both novelty and impact (Ettlie et al., 1984; Dewar and Dutton, 1986; Albert et al., 1991; Gatignon et al., 2002). Expert panels have the advantage of high face validity[3]—who else but experts in an industry would truly know what technological breakthroughs matter to that industry? However, experts may suffer from a number of seemingly unavoidable biases, such as success (or hindsight) bias, recency and availability bias. Success bias indicates that subjects are more aware of technologies that are accepted by the market than those that were not; subjects are also more likely to assign higher ratings of technical value to products with market success (Fischhoff, 1982). Recency and availability biases increase the "score" of a technology one has personally, or recently, been informed of or involved with. In addition, the individual's own involvement means that technologies originating in the organization of the expert assessor are more likely to be recalled in detail (Kahneman and Tversky, 1984). As occurs with hedonic price models, expert panels are likely to confound the economic impact of an invention with its technological radicalness.

*1.1.5. Patent measures*

As patents become increasingly popular, they are being used to capture a wide range of factors regarding inventions and technology; the goal is to evaluate the effect of different technological characteristics on product or firm success (cf. Reitzig, 2003). Two patent measures used to capture radicalness or novelty are: (1) number of times a patent is cited by other, later, patents; and (2) the degree to which the patent classes of cited patents differ from those of the focal patent. Thus the first measure is concerned with forward citations and the latter with backwards citations. Albert et al. (1991) established an empirical relationship between how many times a patent is cited by later patents and the patent's impact, suggesting that forward patent citations capture the impact industry experts assign to an invention. Similarly, Trajtenberg (1990) found that the number of forward citations, weighted by the number of possible citations, correlates positively with the value of an invention. A different interpretation of forward citations is provided by Stuart and Podolny (1996), who argue that there is also a strong social component to a citation. They find that a patent is more likely to be cited if the patent owner holds many prior patents; they also claim that citations are not strict measures of technological content or impact, but also of the patentee's status. Forward citations are therefore a metric of impact, partly due to technical content and partly due to the characteristics of the owner of the patent. We will argue that impact is but one necessary component qualifying an invention as radical.

Recently, patent data has been used to explicitly capture radicalness in inventions using information about backward patent citations. Backwards citations are patents and other documents cited by the focal patent. The theory is that backwards citations to scientific articles measure novelty (Carpenter et al., 1981), since relying directly on scientific literature indicates a greater closeness to science than to the already established technology. Rosenkopf and Nerkar (2001) claim that radical inventions will be more likely to cite patents from other patent classes than from the class to which the radical invention belongs. Since for most technologies, patent classes are defined on the component level, citing patents from other classes involves combining different elements rather than previous inventions (Fleming, 2001). Based on Rosenkopf and Nerkar's idea, Shane (2001) measures the radicalness of a focal patent as the number of three-digit patent classes its cited patents belong to. The advantage of using information about backwards citations is that it is a richer proxy for technical content than forward citations, particularly given patent classes' organization by

[3] Face validity is only concerned with how a measure or procedure appears. It is a direct, but very subjective, measure and does not depend on formal theories or tests for support (Fink, 1995).

technical content. The main drawback relates to the assumptions about the validity of patent classes. Patent classes are determined by the patent office and are reclassified with varying frequency (the more activity in a technology, the more often classes are added or altered); the breadth of a patent class varies greatly across technologies, making cross-technology comparisons difficult.

Using a different view of backwards citations, Ahuja and Lampert (2001) instead simply count the backwards citations. If a patent has zero such citations, thereby citing no prior art, the investigators claim the patent has "no discernible technological antecedents" (ibid., p. 533). When a firm has a large number of such patents, it is considered a pioneer in new technologies. Since many firms deliberately avoid backwards citations (Naiberg, 2003), zero citations may indicate a strategic choice rather than highly novel patents; however, while patent examiners may be duped occasionally and allow no citations, we doubt this can be done systematically. In any case, we think this measure indicates a disconnectedness with past technology and will use it as part of the metric we develop later.

In summary, attempts to measure radical innovation have netted us four practical and four conceptual problems with the current definitions and methods (see summary in Table 2).

The practical problems include: (1) the lack of measures of radicalness; (2) deciding at what point in time two technologies should be compared to one another; (3) finding exhaustive and accessible data sources that model via time-series information about actual technical performance (rate of performance improvements, trajectories, s-curves, and hedonic price models are very data intense, which means that data must be collected from many sources (Coombs et al., 1996)); and (4) finding it costly and sometimes difficult to determine the varying role of performance criteria over time, all as a consequence of the high cost of acquiring technical data over long periods of time.

We also identified four conceptual problems with the existing definitions and methods: (1) performance-comparison issues; (2) impact-based definitions; (3) assumptions of firm homogeneity; and (4) selection bias. We summarize these briefly below and cross-reference them to the methods outlined in Table 2.

### *1.2. Conceptual problems with current schools of thought*

The four conceptual problems we see with the current definitions and methods of measuring radicalness in invention have potentially severe effects on the validity of studies. We discuss these effects below. We end by proposing that an invention's radicalness should be determined by its technical content.

#### *1.2.1. The assumption of performance advantages*

Although the assumption that a new technology should have a performance advantage over the old one is important, it introduces practical as well as conceptual concerns. For example, performance criteria might change, and it is unclear when in time two technologies should be compared. Also, critical performance dimensions tend to change with radical changes, making ex ante identification of the most prominent performance criteria difficult, if not impossible (White, 1978) and, hence, making any performance comparison, by necessity, historical. As for the timing problem, it is a function of the continuous performance improvements of most technologies, old as well as new. For instance, whereas when a radically different invention is introduced, it usually underperforms vis-à-vis the established technology, new technologies might outperform established technologies at a later point in time (Christensen and Rosenbloom, 1995; Dosi, 1982; Foster, 1985). In effect, responses from an expert panel about performance advantages will vary greatly, depending on the maturity of the new technology. Tushman and Anderson's (1986) technology cycle model is sensitive to this issue as well, since one performance index is expected to reflect the shift in technologies when a new one replaces the established one in the market place. Depending on when this shift is considered to have taken place, the ensuing performance improvement will vary in magnitude.

#### *1.2.2. Impact-based definitions*

Basing a radical change's definition on its impact on incumbent firms in an industry (Anderson and Tushman, 1990; Dewar and Dutton, 1986; Ettlie et al., 1984; Henderson, 1993; Tripsas, 1997) is problematic since the various outcomes of introducing a radical technological change is at the same time likely to depend on the firm's characteristics. For example, how

Table 2
Summary of practical and conceptual problems using different methods

| | Technology cycles | Trajectories/s-curves | Hedonic price-models | Expert panels | Patent measures |
|---|---|---|---|---|---|
| Practical problems | | | | | |
| 1. Lacks quantifiable measurement indicating when an invention is radical | No—order-of-magnitude change in performance = radical | Yes—need expert help to determine if a new trajectory/curve is started | Yes—focuses on price increases as a function 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 |
| 2. Difficulty of timing—when to compare innovations | Yes—no a priori metric | 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 |
| 3. Difficulty in accessing data | Difficult | Difficult | Medium difficulty | Easy | Easy |
| 4. A priori key characteristic determined? | No—performance criteria can vary | Yes—model is predefined as effort and technical impact | No—models are variable | No—varies from expert to expert | Yes—patents citations |
| Conceptual problems | | | | | |
| 1. Performance-comparison issues | Yes—assumes performance criterion stable | 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 |
| 2. Impact-based definition | Yes—second dimension (competence enhancing /destroying) is an impact dimension | 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 |
| 3. Assumptions of firm homogeneity | Yes—competence assumed homogenous across incumbents | No | No—focus on product characteristics | Standard questions have impact bias, could be removed | Yes—for forward citations, ignoring the likelihood of being cited is a function of firm status; No—for backwards citations |
| 4. Selection bias | Yes—only inventions with market success included | 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 |

well a firm deals with radical technological change may be a function of the firm's prior knowledge. Thus, it would be incorrect to base the definition of the exogenous shock on its outcome.

### 1.2.3. Assumption of firm homogeneity

The decision to base a radical change's definition on whether it enhances or destroys knowledge assumes that all established firms in an industry are equally influenced by this new technology. Note, however, that this supposition of firm homogeneity is only made with respect to prior knowledge; it does not apply to other firm characteristics (such as firm tenure). Moreover, those other firm characteristics are used as predictors of success while they are likely at the same time to be highly correlated with the level of prior knowledge. Hence, we face endogeneity problems if we use a definition requiring competence destruction.

### 1.2.4. Selection bias

Most studies show a selection bias since we lack ways to detect and include unsuccessful radical inventions; indeed, most findings only hold for successful technologies that have a significant market impact (Fischhoff, 1982; Tellis and Golder, 1996; van de Poel, 2003).

We suggest a straightforward way for solving many of the practical and conceptual problems that occur with currently used definitions and measurements. That is, define radicalness based on technical content and the ways in which an invention's technological content differs from the already existing technology. In Section 2, we outline three criteria for identifying a successful radical technological invention; we posit that an invention fulfilling two of these criteria can be identified as a failed radical invention.

## 2. Defining and measuring radicalness using technical content

We focus here on developing a method that avoids the methodological problems that have plagued past investigators trying to identify radical technological changes. We propose a method for identifying inventions that although they have the potential to affect change within an industry, do not necessarily succeed in doing so. In addition, we propose a definition that is focused on technical content; does not make any assumption about firm homogeneity; is independent of the technology's impact on competitive and market conditions; and, finally, is relatively insensitive to when inventions are compared. Hopefully, this will allow us to make prospective judgments about the radicalness of an invention at the actual time it is introduced in a patent, or as part of a product in the market.

### 2.1. Defining radicalness

While most industries face a stream of inventions over time, a very small subset of these has the ability to single-handedly reconfigure the industry's bases of competition. We argue that there is not only a way to ex ante identify whether an invention is radical, but also a way to ex post systematically analyze a product market to determine whether an invention was an important change agent or just a potential vehicle for change.

But what does it mean for an invention to be deemed radical? Studies focusing on sources of novelty argue that radical novelty is achieved through recombining already established elements (Fleming, 2001) or by introducing an established element into a new setting (Hargadon and Sutton, 1997). In both cases, the investigators imply that radicalness is a combination of elements and settings not previously observed. Thus, in addition to considering recombining and bringing in foreign elements, we must consider constant invention within an industry that goes beyond simple recombination (van de Poel, 2003), one that allows for the creation of new elements. In short, regardless of the source, one can say that a radical invention is something novel, that it has distinctive features missing in previously observed inventions.

Further, most discussions around radical innovations assume that there is one determining invention that initiates a new technological trajectory; and that this particular invention, not previously observed in that particular setting, either starts the chain of improvements or constitutes the core of the change (Silverberg, 2002). Overall, studies focused on radical innovation fit in the "punctuated equilibrium" set of theories that expect one key event, unique to the time and setting, to alter the nature of things to come (Gersick, 1991). To be equally general, we base our definition on the expectation of a unique event.

Finally, a key radical invention should influence future inventions; that is, affect future technical content. A growing body of evidence notes that a particular invention is the change agent in existing industries, or the starting point for new industries, often championed by an individual or organization that will not manage to reap any economic benefits from it (Tellis and Golder, 1996). Furthermore, the initial invention itself is usually not the finished product that is brought to market. Despite many radical inventions failing in their early incarnations, the key ideas behind the invention might end up having a great impact on the elements and the combinations of elements used in ensuing inventions. Thus, by having an impact on future technical content, a radical invention might still transform technology, even if early manifestations fail. By keeping the focus on technological impact rather than on market impact, firm survival, or price-performance aspects, we avoid problems with outcome-based impact measures that expect the change agent itself to be successful.

Based on the above reasoning, we argue that for an invention to be considered radical it has to fulfill three criteria:

Criterion 1: The invention must be novel: it needs to be dissimilar from prior inventions.
Criterion 2: The invention must be unique: it needs to be dissimilar from current inventions.
Criterion 3: The invention must be adopted: it needs to influence the content of future inventions.

If an invention fulfills criteria 1 and 2, one can ex ante claim that it is a radical invention. If it also fulfills criterion 3, one can ex post claim that it is a successful change agent, causing a radical technological change in an industry.[4]

The three criteria suggest three time periods that must be used to analyze each invention: past, present, and future. At each time period, the invention is determined to be either similar or dissimilar to other inventions. The most common characterization would be that of status quo; namely, a focal invention that is similar to inventions in the past, similar to current inventions, and similar to inventions in the future. Another possible characterization would be that of a failed radical change: an invention appears that is different from past and current inventions, but has not been adopted by future developers and ends up not being a change agent. In other words, future inventions are dissimilar from the focal invention and the invention ends up as an isolate. By identifying failed, but potentially radical, inventions, one can study the factors that explain how radical inventions succeed either in the market place or just as change agents. Finally, the most important characterization would be that of the successful radical invention, whereby the focal invention is dissimilar to both past and current inventions. Note, however, that the future inventions would be similar to the focal invention, since these future inventions are inspired by the radical invention.

### 2.2. Operationalizing the definition

To implement and test the three criteria for radicalness, we suggest using patent data. Patent data have several attractive features. They do not suffer from retrospective bias since they are collected continuously; moreover, because the information in a patent has to comply with a fixed format, they are systematic. Patent data do not suffer from success bias—patents are filed prior to commercialization, or, at least, before the commercialization outcome is perfectly known.[5] Patents are evaluated by a patent office examiner, who makes sure that the inventions outlined in a patent satisfy the requirements of novelty, non-obviousness, and usefulness. Finally, even though patenting rates differ across industries and over time, they seem to be fairly consistent *within* industries (Cohen et al., 2000), making it possible to conduct within-industry comparisons of radicalness using patents.

Our first criterion for a radical change is novelty. Since we are using patent data to measure novelty, we must make a distinction between what we mean by novelty and what patent offices mean by novelty. Novelty is one of three requirements for receiving a patent. While all patented inventions meet a minimum level of novelty, different degrees of novelty exist among patented inventions[6] (cf. Reitzig, 2003; Shane,

[4] We hesitate to call even an invention that fulfills all three criteria an innovation; it might be a change agent but still fail to be commercialized.

[5] According to US patent law, an inventor has one year from disclosing the content of an invention to file for a patent.

[6] In fact, different national patent offices seem to have different views of what constitutes a minimum level of novelty. The Cana-

2001; Fleming, 2001). To term an invention radically novel, we expect a higher degree of novelty than is required to be granted a patent.

Let us return to our notion of novelty. Differences in novelty across patents have been measured using the prior art cited by a patent in order to understand how a new invention differs from previous ones (cf. Ahuja and Lampert, 2001; Rosenkopf and Nerkar, 2001; Shane, 2001; Podolny and Stuart, 1995). Novelty is, by definition, a relative measure and, as proposed in criteria 1 and 2, can only be determined in relationship to what has come before it and what is occurring simultaneously. We suggest studying the similarity of patents' citations, or rather, the degree to which inventions resemble or differ in citation structures. Our reasoning is that differences in citation structures across patents indicate differences in the knowledge that inventions rely upon (Jaffe, 1986; Reitzig, 2003; Stuart, 1998; Rosenkopf and Nerkar, 2001), while similarities suggest that similar, or identical, elements have been included, thereby offering more limited novelty. The list of referenced patents bounds the focal patent and also shows what previous ideas the invention rests upon. References in a patent are similar to those in a research article. However, legal requirements are laid out as to what must be cited in a patent. First, an inventor is required by law to list relevant prior art. In addition to citations made by the inventor, a patent examiner reviews the patent application at the patent office; he or she performs an independent search for related prior art. The degree of independence between these reference sources is particularly appreciated when one realizes that the majority of references are added by the examiners (as reported by, for instance, the Derwent Innovations Index Patent database).

#### 2.2.1. *Mapping citation patterns to criteria of novelty, uniqeness, and impact*

In this section, we discuss how citation patterns are expected to map onto the three criteria for radicalness. We base our discussion on theories about sources of novelty (Fleming, 2001; Hargadon and Sutton, 1997).

We expect citation patterns to mirror the source of radicalness—the introduction of established elements into a new setting or the recombination of previously used elements. When the source of radicalness is the introduction of an established element into a new setting (Hargadon and Sutton, 1997), ensuing citations should either contain very few citations, which would indicate a high level of novelty since nothing coming before has any bearing on the invention (Ahuja and Lampert, 2001); or contain citations related to the field the element was used in before. In both these cases, we expect radical patent citations to differ from those elicited from incremental inventions following an established technological trajectory. For example, when the source of radicalness is a recombination of previously used elements, we would expect a recombination of citations; in other words, many citations might have been used before but not in the combination observed for the radical invention. Again, we would expect a difference between citations for radical and normal invention patents. Thus criteria 1 and 2 of our definition of radicalness—the novelty and uniqueness requirements—can be translated as follows: "The higher the novelty of an invention, the more different the patent citation structure should be from previous and concurrent inventions.[7]"

With respect to criterion 3—impact on future technological content—we expect the novel citation pattern to be mimicked by inventions trying to emulate the core ideas of the radical invention. An invention that recombines elements in a radically novel way stands out in the normal stream of inventions. When the invention is before its time, its inventor has low status (Podolny and Stuart, 1995), or the improvement has limited practical value, its technical content is likely to have a limited impact on ensuing inventions. However, when a radically novel invention is timely and solves a technical problem with value going either to other inventors or to a segment of the market, the ideas in

dian patent office denied a recently granted US patent for the "sealed crustless sandwich," US Patent 6,004,596 (see The Economist, 2004; Shulman, 2001, for commentary) for not meeting the office's novelty and non-obviousness demands. Similarly, although Howard Head was granted a US patent for the oversized tennis racket in 1976 (despite size being explicitly termed "non-patentable"), he was unable to patent this feature in West Germany or Japan.

[7] We do not claim that all differences in citation patterns are a function of underlying technical differences. For instance, as discussed elsewhere, there is evidence of social factors influencing both what citations are chosen and what technology firms pursue (Podolny and Stuart, 1995). Other possible influential factors might include examiner preferences, how well informed inventors (or their patent agents) are, etc.

the invention are more likely to be elaborated upon; we would then expect inventions based on the same elements or combinations of elements. Using the terminology of trajectories, the radical invention can be said to start a new trajectory; if it becomes successful, we will see a corresponding stream of normal inventions. Thus, criterion 3, requiring adoption, can be expressed as *the more successful the novel invention, the more similar the citation structures of future patents would be to the citation pattern of the novel invention*.

In the next section, we operationalize the definition of radical change and generate measures that need to hold in order for the three criteria to be fulfilled.

### *2.2.2. Operationalizing the criteria measuring similarity in citations*

In the preceding section, we formulated how the three criteria for radicalness map to expected citation patterns. We develop tests for all three criteria, using a measure of similarity in patent citations based on backwards citations. Two of our three criteria can be tested at the time a patent is granted and before any impact is observed; this allows for the possible identification of radical invention at an early stage. To quantify the criteria, we develop a measure indicating the degree of similarity between any two patents. We extend the results by summing this similarity for all other patents for each focal patent within each year. Controlling for the number of patents in each year, we can then compare the similarity of patents, one to one another, with respect to the citations they contain (Stuart, 1998; Stuart and Podolny, 1996).

To compare how citations of two patents $i$ and $j$ overlap, we compute an overlap score of $i$ and $j$, $\mathrm{os}_{ij}$, as the number of patents cited by both patent $i$ and patent $j$ divided by the number of patents cited by $i$ and $j$. Or, in more formal terms: let us consider patent $i$, issued at time $t_0$, and patent $j$ issued at time $t_j$. Let $i_c$ be the set of patents cited by patent $i$, and let $j_c$ be the set of patents cited by patent $j$: the set $i_c \cap j_c$ is the set of patents both $i$ and $j$ cite and the set $i_c \cup j_c$ is the set either of them cite. If the number of jointly cited patents $i_c \cap j_c$ is $x$ and the number of separately cited patents $i_c \cup j_c$ is $u$, then: $\mathrm{os}_{ij} = [i_c \cap j_c]/[i_c \cup j_c] = x/u$. Then $\mathrm{os}_{ij}$ can take values between 0 and 1, where 0 indicates "completely dissimilar" and 1 indicates "identical" citation patterns. See Appendix A for an illustration of how $\mathrm{os}_{ij}$ is computed.

We can construct $i$'s overlap score for all patents $j$ issued in some year $t$ by taking the overlap score between $i$ and each patent $j$ issued in $t$. For instance, we can compare patent $i$ issued in year $t_0 = 1980$ to all patents $j$ issued in 1985, by summing patent $i$'s overlap scores across all dyads with patents $j$ issued in year $t = 1985$ into an annual overall score, $\sum_j \mathrm{os}_{tij} = \mathrm{os}_{ti}$. For criterion 1, we are interested in comparing patent $i$ with all patents $j$ issued in $t < t_0$ for comparisons to patents preceding $i$. For criterion 2, we are interested in comparing patent $i$ with all patents $j \neq i$ issued at $t = t_0$ for comparison to patents issued the same years as $i$. Finally, for criterion 3, we are interested in comparing patent $i$ with all patents $j$ issued in $t > t_0$ for comparison to patents succeeding $i$. Since the total number of patents in a year, $n_t$, will have a great impact on the possible size of $\mathrm{os}_{ti}$, we divide $\mathrm{os}_{ti}$ by the number of patents issued in that year, creating $\mathrm{os}_{ti}/n_t$.

If patent $j$ is issued in $t_j < t_0$, that is, earlier than the focal patent $i$, then $i$ and $j$'s citations can only overlap for years $\tau \leq t_j$, that is, the period before both patents have been granted. Similarly, if patent $j$ is issued in $t_j > t_0$, citations can only overlap for years $\tau < t_0$. Citations are therefore only compared for years $\tau < \min[t_0, t_j]$.

Remembering that a patent's annual overlap score is the comparison between that patent $i$ and all patents $j \neq i$ issued in year $t$, we can use the single measure of a patent's annual overlap score to formulate three empirical criteria that match the three theoretical criteria:

Criterion 1: A radical patent's citation structure should be dissimilar to the citation structures of past patents. That is, $\mathrm{os}_{ti}/n_t$ should be low for $t < t_0$.
Criterion 2: A radical patent's citation structure should be dissimilar to concurrent patents' citation structures. That is $\mathrm{os}_{ti}/n_t$ should be low for $t = t_0$.
Criterion 3: A successful radical patent's citation structure will become replicated in the future. That is $\mathrm{os}_{ti}/n_t$ should be high for $t > t_0$.

In many situations, criteria 1–3 can be applied directly to identify radical inventions; we look for patents that satisfy criteria 1 and 2 first, and then add criterion 3 to capture successful inventions. In addition, criteria 1 and 2 can be used at the time a patent is granted, often before an invention has reached the market, allowing for ex ante identification of potential radical inventions.

Below we will use some shortcuts to simplify the method by combining and developing the criteria. If the objective is to identify radical inventions after their impact can be observed, we can collapse criteria 1 and 3 into one condition, simply stating that a patent's future overlap should be greater than its past overlap for the period $t_0 - p$ years in the past and $t_0 + p$ years into the future:

$$\sum_{t_0-p}^{t_0-1} \sum_j \left(\frac{\mathrm{os}_{tij}}{n_t}\right) = \sum_{t_0+1}^{t_0+p} \sum_j \left(\frac{\mathrm{os}_{tij}}{n_t}\right) \tag{A}$$

Criterion 2 can be seen as the search for patents with the lowest overlap score for their grant year, expressed as:

$$K = \min \left\{ \frac{\mathrm{os}_{t_0 i}}{n_{t_0}} \right\} \tag{B}$$

Once patents are identified that fulfill conditions (A) and (B), future overlap scores can be further analyzed. Successful radical inventions should exhibit overlap scores that increase over time as the impact of the radical invention takes off, providing an extension of criterion 3:

$$\frac{\mathrm{os}_{ti}}{n_t} < \frac{\mathrm{os}_{(t+r)i}}{n_{t+r}}, \quad \text{when } t > t_0 \quad \text{and} \quad r > 0 \tag{C}$$

A practical way to make this comparison is to first combine conditions (A) and (C) in order to compare patent $i$'s overlap scores for 1 year prior to granting with 1 year after granting; then for 2 years prior to granting compared to 2 years after granting, etc. Then, for each year of comparison, select the top 10% of all patents that fulfill corollary (C.1):

$$\frac{\mathrm{os}_{(t_0-p)i}}{n_{t-p}} > \frac{\mathrm{os}_{(t_0+f)i}}{n_{t+f}}, \quad \text{for } f = p \quad \text{and} \quad f = [1, 5] \tag{C.1}$$

In corollary (C.1) $f$ and $p$ are assumed to be equal, but this is a restriction that can be relaxed, allowing $f > p$ for science-based, more slow-diffusing technologies, for instance. For a patent to fulfill condition (C) and corollary (C.1), it needs to demonstrate increasing overlap scores following the grant year of a patent as compared to the year preceding the grant year of the patent. We chose, as a first test, to compare overlap scores for $\pm 1$ years, $\pm 2$ years, etc. However, a lag might manifest before a radical innovation is imitated, since it might not immediately be identified as interesting and not even commercialized, in which case the choice of $p = f$ might not be reasonable. In addition, when another radical invention appears, the overlap with other patents might drop again as patents are filed that mimick new invention citations instead. This is why we will put a time limit on $f$ and $p$ of 5 years when applying the method to a data set in the next section.

To illustrate the overlap scores, Fig. 1 contains graphs over time for three different patents labeled: radical, incremental and failed (potentially radical).

## 3. Applying the definition and measure to tennis racket inventions

For this study, we decided to use 581 patents from 1971 to 2001 in one product class—tennis rackets. The tennis rackets product class is a useful example, previous work having indicated two successful, and unknown numbers of unsuccessful, radical changes in this time period (Andrews, 1994; Ashley, 1993; Chen, 1998; Dahlin, 2001; Wendland, 1986;). Further, it is a product class with a high patenting propensity (Chen, 1998).

### 3.1. Results

Dyadic overlap scores are computed for all tennis racket patents, in total $581 \times 580$ computations, thus making all possible comparisons between any two patents in the data set.[8,9] The dyadic values are summarized into yearly measures of how similar patent $i$ is to all other patents $j \neq i$ in the year $t_0$ that $i$ was granted; how similar patent $i$ is to patents $j$ granted $t = t_0 + 1$, $t_0 + 2, \ldots, t_0 + f$ years into the future; and to $t = t_0 - 1$, $t_0 - 2, \ldots, t_0 - p$ years into the past. Since the data covers 1971–2001, $f + p + t_0 = 31$ for all patents in the data set. Graphing the annual overlap scores in relationship to when patents are granted in Fig. 2, we find that scores peak for the year of granting. This suggests that patents are more similar to other patents issued at the

[8] We elected to analyze US backwards citations in this set of analyses. US citations dominate the total number of citations in the data set; it also appears that foreign citation are becoming more common over time, which is why we were concerned with time-effects if we included them.

[9] Programs, written for the software package Mathematica, generating the overlap scores, as well as programs in STATA, performing the tests, are available from the first author.

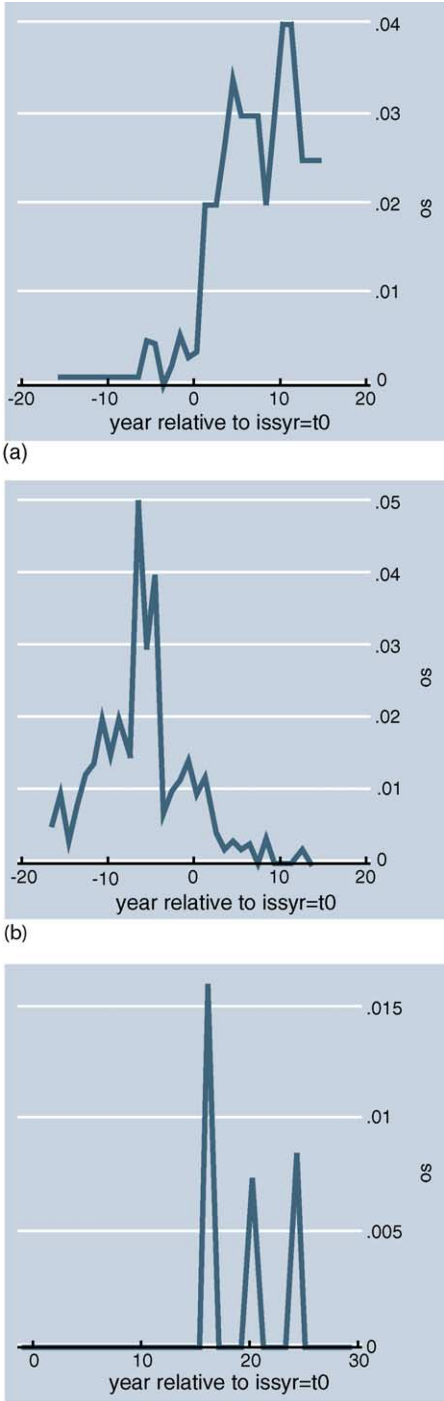


Fig. 1. Typical patterns of overlap scores over time for (a) a radical; (b) an incremental; and (c) a failed (potentially radical) invention.

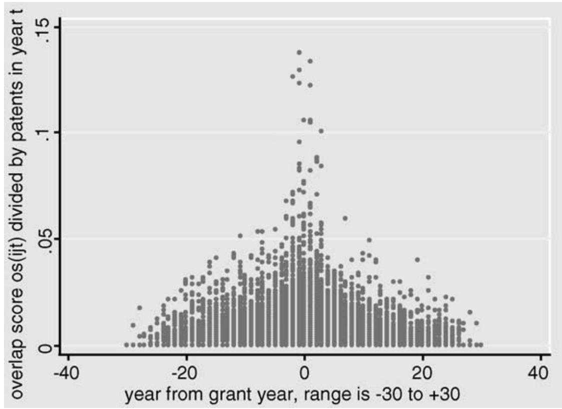


Fig. 2. Distribution of overlap scores in relationship to the year a patent is granted (please note that each patent is represented with 31 data points, giving $581 \times 31 = 18011$ values in the graph).

same time (also see Table 3 for descriptive statistics). The steep drop-off in scores at the ends of the distribution shows that the data is unbalanced: there will be fewer observations as $f$ and $p$ approach 30. Since we rank differences in overlap scores (1 year into the future, 1 year into the past), we decide to standardize the overlap scores within each year, relative to that of a patent's grant year. This will have the benefit of not overstating differences due to low variance. Thus, from each individual patent's score $\mathrm{os}_{t_0 \pm p}/n_t$ is subtracted the mean value of the population's score for $t_0 \pm p$, which is then divided by the standard deviation of the annual overlap score for the same $t_0 \pm p$. The standardization leads to a mean value within each distance from $t_0$ of zero, and a standard deviation of 1. Graphing the standardized scores over time relative to the patents' grant year, we now have a more uniform distribution, with blunt rather than pointed tails, since we force the standard deviation to be the same across years.

Condition (A) will be subsumed by corollary (C.1), and we first apply condition (B), looking for uniqueness. We denote patents as unique if they either have an annual overlap score of zero for year $t_0$, their grant year (that is, the lowest possible value); or they are among the bottom 10% of patents with respect to their standardized score. We end up with 118 patents that satisfy these uniqueness criteria, representing about 20% of the population (about 10% of all patents had $\mathrm{os}_{it}/n_t$ score of zero, and we allowed for the second decile of low scores to be included as well).

Table 3
Some descriptive statistics for the population of 581 tennis racket patents

| Variable | Mean | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|
| Grant year | 1986.7 | 7.87 | 1971 | 2001 |
| Number of patents granted per year | 18.74 | 9.04 | 7 | 41 |
| Overlap score, $os_{it}$ | .089 | .15 | 0 | 1.72 |
| Annual overlap score, $os_{it}/n_t$ | .005 | .008 | 0 | .14 |

Corollary (C.1) yields five lists, one for each time period of comparison of standardized overlap scores (1 year after granting versus 1 year before granting, 2 years after granting versus 2 years before granting, and so on), from which we select the top 10% patents as a first approximation, since we expect far fewer than 10% of all patents to be radical. Each time a patent shows up among the top 10% of patents on one of the five lists, we give it a score of 1. After adding up the scores, requiring a patent to end up at least once among the top 10% of patents in any one of the five lists, and applying corollary (C.1), we end up with a list of 25 patents that are unique, novel, and have impact. Because 25 patents represent about 4% of the data set of 581 patents, a greater proportion of patents than we can reasonably label radical, we broaden the requirement: now a patent must show up at least twice on the top 10% lists. The more stringent requirement reduces the list of patents to six, or about 1%. Over a period of 31 years, we consider six possible radical inventions to be a more reasonable number than 25, since 25 would suggest almost one radical invention per year. Compared to other longitudinal studies with multiple successful radical innovations, these studies typically report that such innovations occur at a rate of from one per 5 years to one per 33 years. Witness Tushman and Anderson (1986), who found one successful discontinuity every 15–25 years in the cement, airline and minicomputer industries. Similarly, Tripsas (1997) outlined the presence of three product generations over 100 years in the typesetting industry, and Henderson (1993) discussed five successful radical innovations over a 28-year period in the photolithographic alignment industry.

What do the six patents touch on? Table 4 lists the patent number, grant year, and title for each of these patents. Two of them—number 3,999,756 entitled *Tennis racket,* and number 4,664,380 entitled *Racket having thickened shaft portion*—describe the two inventions generally identified by experts as those transforming tennis racket design during our period of study (Chen, 1998; Ashley, 1993; Wendland, 1986; Andrews, 1994). Patent number 3,999,756 outlines the oversized racket, which moved the surface area of the average racket head from about 70 to 110 in.$^2$. This patent launched Prince Mfg. Inc. onto the racket market and gave the company about 30% market share within 3 years. Patent number 4,664,380 transformed the physics of tennis rackets by making racket frames stiffer, thereby allowing for much more hard-hitting rackets. The patent was licensed across the world by Wilson Sporting Goods, who named the first model based on this technology "The Hammer."

It is comforting that these two, generally considered the most important inventions of the 1970s and 1980s, were identified using the overlap scores; such an identification provides external validity for our measure. Even more interesting are the four other identified inventions; we suspect that among them may be some radical inventions that might fulfill the novelty and uniqueness criteria, although not that of impact. Bibliographic information is provided in Table 4. We refer to one manufacturing invention, one stringing invention, and two handle inventions. An interesting point is that two of the four patents are so-called submarine patents (cf. Graham and Mowery, 2004); that is, patents that use continuations, or adjustments to the original filing that restart the patent clock; thus the invention is kept secret for a long period of time before it surfaces, thereby allowing its owner to pursue his or her monopoly rights.[10] Overall, the effect is to extend the patent life, or delay the patent protection period until the invention might have a higher market value. Submarine patents

[10] Since 2001, even non-granted patents are disclosed after 18 months with the US patent office. Thus the practice has become less common (Graham and Mowery, 2004).

Table 4
Patents identified as possible radical change patents, fulfilling the criteria of novelty, uniqueness and impact

| Patent number | Grant year | Patent title | Comment |
|---|---|---|---|
| 3999756 | 1976 | Tennis racket | The oversized racket revolutionized racket design. Very strong patent, upheld in at least one law suit. The underlying invention huge market success—took 30% of premium racket market within 3 years. |
| 4366959 | 1981 | Racket for tennis and similar games | Stringing pattern with denser stringing in sweet spot area in center of racket head. Submarine patent (two continuations, one abandoned). Inventor is Renee Lacoste, the father of the materials revolution in tennis rackets in the 1960s. This patent appears to be a broad-claims patent. |
| 4614626 | 1986 | Method for fabricating a tennis racquet frame | Internally strung graphite frame, strings do not exit the frame to the outside of racket head. Mix of product and process claims. |
| 4664380 | 1987 | Racket with thickened shaft portion | Wide body racket design that changed racket design to stiffer rackets. Inventor is Siegfried Kuebler. Invention licensed to Wilson Sporting goods and launched their Hammer racket series. |
| 4906002 | 1990 | Racquet with reinforced throat detachable handle | Main objective is to achieve a well-playing racket that takes less space when stored and when traveling. Novel since only two prior similar inventions, both with low playability. Unique—no similar patent in grant year. Uncertain whether it has had any impact. |
| 5409216 | 1995 | Racket handle | Handle can rotate into multiple positions and then be locked into this position. Permits customization. Indication of value: this is a so-called submarine patent, first version filed in 1984, granted patent finally filed in 1992. |

have been found to be more cited than non-submarines (Simcoe, 2005); it appears that, generally, the longer time it takes a patent to go from initial filing to granting, the more cited it ends up, thus signifying social value (Johnson and Popp, 2001). The submarine patents we identified are patent number 5,409,216 (*Racket handle*) and patent number 4,366,959 (*Racket for tennis and similar game*). The first of these was originally filed in 1984, lists seven abandoned filings, and was granted in 1995. The second, originally filed in 1978, lists two abandoned filings, and was granted in 1983. The latter patent describes an invention that varies the density of strings across the racket head. The inventor is Renee Lacoste, former tennis star and the father of the Wilson T2000 steel racket, patented in 1963 and introduced into the US market 3 years later, at which point it started the innovation craze in tennis rackets (Dahlin, 2001). Overall, the information about these two patents suggest that they might be important in the industry, if not as visible as the oversized and wide-body racket inventions.

In the next section, we compare the method that uses overlap scores with one that uses direct forward citation counts. We argue not only that the two methods capture different aspects of patent impact, but that they can be combined to increase our understanding of radical technological change.

### *3.2. Sensitivity analysis—comparison to patent-based measures*

In order to determine whether the three criteria capture different information than the more simple-to-use count of forward citations, we compare the forward citations count for the top six identified patents with the rest of the sample. Performing a chi-square test, we find that the top six radical patents demonstrate a statistically significant distribution of forward citations, as compared to those not among the top six ($\chi^2(25) = 147.7, p < .01$). Those top six patents received an average of 9.50 citations, while patents not among the top six received an average of 3.86 citations. The standard deviation was also much higher for the first than for the second group: 10.97 versus 4.40, suggesting that some of the inventions we identified, although without the great impact as measured by forward patent

Table 5
Most cited patents using direct citation counts

| Patent number | Grant year | Forward citation count | Identified by three-criteria method |
|---|---|---|---|
| 3647211 | 1972 | 30 | No |
| 3801099 | 1974 | 26 | No |
| 4165071 | 1979 | 26 | No |
| 3999756 | 1976 | 25 | Yes |
| 3582073 | 1971 | 24 | No |
| 3642283 | 1972 | 22 | No |
| 4664380 | 1987 | 22 | Yes |

citations, are in the sample for reasons of novelty and uniqueness.[11]

As a second comparison, we compared the seven patents with the highest forward citation count (since number six and seven had the same number of forwards citations, we include them both) with the top six radical patents identified. We discover that the two historically recognized radical innovations are identified by both methods (ranked fourth and sixth/seventh) and that the others are unique. Thus both methods allow for the determination of extreme- and high-impact radical innovations, but differ in terms of how they rank other inventions (Table 5).

The two methods also differ in terms of temporal emphasis. Whereas direct citation counts tend to favor older patents, with the mean issue year for the top seven cited patents being 1975.9, our method does not favor older over newer patents, with the mean issue year for the top six being 1986.2; this represents a difference in age of 10.3 years. In fact, the patents identified by direct citation counts are, on average, significantly older than the population as a whole ($t = -3.69$, $p < .01$), while the patents identified using overlap scores are not ($t = .10$, $p < .92$). This difference in temporal emphasis demonstrates one of the weaknesses of using citation counts: a reasonably long period of time must pass before we can see whether a patent is cited.

Finally, we use two other patent-based measures of radicalness to see how well key tennis racket inventions are identified. We find that applying Rosenkopf and Nerkar's (2001) measure of radicalness to the tennis racket data set, a measure requiring a patent to cite patents from other classes than the one it belongs to, does not identify either the oversized or the wide-body racket as radical; indeed, all citations made in these two patents are from within the same three-digit class they are assigned to. The few patents that cite beyond that data set direct their citations to materials manufacturing classes (for instance, patent 4,614,626, among our top six, cites five patents from class 264, "Plastic and non-metal article shaping or treating: processes"). Similarly, applying the Ahuja and Lampert (2001) measure, which states that zero backwards citations is a measure of novelty, would mean that neither of the two successful, radical tennis racket inventions would be identified. Both have backwards citations: 10 US and 4 non-US for patent 3,999,756 and 11 US and 2 non-US for patent 4,664,380.

## 4. Conclusions and discussion

In this paper we developed a new and clear definition of radical invention based on the technical content of inventions. First, we require a radical invention to have dissimilar content compared to older inventions; second, we require the invention to differ from existing inventions; and third, for a technically successful radical invention, we require that it affect the contents of future inventions. This three-stage definition has a number of advantages over existing definitions. For one thing, it explicitly focuses on technical content and is specific about time effects. It also resolves most problems of previous definitions, many of which confounded the definition and measurement of radicalness with its outcomes, were highly situation-specific, and were difficult to operationalize. We found that using patent data or, more specifically, patent backwards citations to measure the three criteria, further strengthened the usefulness of the definition, and for several reasons. First,

[11] Using the same comparison method for the larger group of 25 patents, we find that these are also more highly cited than the average patent ($\chi^2(25) = 69.00$, $p < 0.01$). The mean number of citations for the top 25 patents is 6.24, with a standard deviation of 7.13.

archival data remove problems plaguing measures that rely on human experts, such as retrospective and hindsight biases. In addition, patent data are both easily accessible and usable across settings, making the method more generalizable. An advantage of the three-pronged definition with respect to the past, the present, and the future is that the past and present are immediately available. That is, our measures can be used to identify potential radical inventions as they appear, making this a useful tool for researchers and managers alike. Another key contribution is that our measure is able to identify technologically radical patents, even though they are not commercially successful, which should help alleviate selection biases in academic studies. In addition, being able to identify failed radical inventions allows us to start developing stronger models for predicting success of radical inventions (Freeman and Soete, 1997).

We tested the metrics on a relatively small data set containing all 581 tennis racket patents granted in the US over 31 years. With the mathematical conditions we developed, we were able to identify six patents, two of which (the oversized and the wide-body racket) are generally considered to be the most novel and to have the greatest technical impact as described by tennis historians. Of the four remaining patents, two were submarine patents, which are usually found to be of high value (Graham and Mowery, 2004; Simcoe, 2005).

While the logic behind our method is straightforward, it still faces empirical challenges. As with most methods, the question is what cut-off point to use to turn a quasi-continuous measure into a dichotomous one. In the example provided, we illustrated how each added condition would exclude an increasing number of patents. We added conditions until we thought we had a reasonable number of inventions to investigate; in this case, we thought 25 was too large a number as it suggests one potential radical invention every 1–2 years, a far greater number than that of previous studies (which report some 5–33 years between successful radical inventions); six in a 30-year period was probably still a number large enough to include less radical or failed radical inventions as well as key inventions.

In some technologies, inventions are described in a series of patents rather than just one. Although the assumption we make about one invention equalling one patent does hold for simple and relatively discrete technologies (such as tennis rackets), it is violated for many complex technologies, where an invention might be described in a series of patents.[12] One way to deal with this problem is to analyze patent families; if a series of patents from the same patentee have the same filing date and refer to one another, they can treated as one invention.

A natural limitation of our measure is the reliance on patent data, which means that assumptions are made about radical inventions being patented. In industries where patenting frequencies are low or when a radical invention stems from an inventor without the interest, or means, to patent it, our method is obviously inappropriate. But having said that, we still argue that the definition of radicalness is useful even when its operationalization is irrelevant.

How efficient are our measures and what advantages do they provide over other patent-based measures? We made explicit comparisons to direct citation counts in Section 3.2. We found that although both methods were able to identify the radical patents repeatedly identified by industry experts, the rest of each method's top four patents were unrelated. The agreement is somewhat lower than we had expected: 2 of 10 inventions are shared (20%), whereas we expected about a third to be shared across the two methods. The low agreement suggests that the way we measure impact captures a different aspect of impact than that captured by citation counts.

Having established that forward citation counts and overlap scores capture different aspects of patents' importance within a technology, we need to consider the conceptual differences between the two methods. Forward citations indicate the impact a patent has had in an industry (Albert et al., 1991), but provide no idea of whether the impact is due to the invention's technical content being radical. In fact, the social constructivist view of patent citations insists that a patent is more likely to be cited if the owner has a high status within an industry (Podolny and Stuart, 1995); this indicates

[12] In pharmaceuticals, for instance, a new product often requires three patents: one for the molecule and its variants, one for the mix of critical and non-critical ingredients, and one for the use of the molecule. In addition, some complex mechanical inventions are outlined in two or more patents. The number of patent claims influences the cost of the patent; at times it is more favorable to split claims into multiple patents.

not only that visibility is an important factor that influences whether others are willing to patent in the same realm, but that visibility might come with belonging to a large, successful firm.

We found as well that two other patent measures aimed at capturing novelty are unable to identify even the successful radical inventions. We therefore claim that the relative ease of use of our method, as compared to that of non-patent-based methods, makes it preferable to those, while its combined ability to detect successful and unsuccessful radical patents makes it preferable to other patent-based methods.

### 4.1. Future work

We see two directions for future work. The first is directed towards further establishing the reliability and generalizability of the overlap measure. Hence, applying the method to other technologies as different from tennis rackets as possible is a first step. That involves testing different conditions and varied cut-off points. In this study, we used a very conservative test that restricted the number of patents in our final set. Relaxing the conditions would have allowed a broader search for key inventions.

On a more conceptual note, what does it mean when a patent not only shares backwards citations with another patent but also cites that patent? Right now, we treat that citation as a non-overlap. But is this the correct way to view it? Some scholars suggest that a cited paper also encompasses all papers cited by it; that is, if paper A cites paper B and paper B cites papers C and D, then paper A indirectly cites papers C and D (Salancik, 1986). It would be interesting to explore the indirect citation paths further to see if they add any additional insights. We suspect that indirect citations are more of an issue for the impact part of a patent than for the aspects of either novelty or uniqueness.

A second direction is to re-evaluate known data sets where the effects of radical changes have been tested. By including unsuccessful changes, we can study factors that make a radical invention successful; for instance, we might test the idea that patentee status may be a determining factor (Podolny and Stuart, 1995). Other interesting questions concern the timing of the conception of potentially radical inventions. It would seem reasonable that ideas presented in times of munificence (market growth, for instance) would have a far greater chance of succeeding if that same invention were presented when the industry is in decline. By including successful as well as unsuccessful potentially radical inventions in an analysis and using indicators of technical and/or market success for inventions as dependent variables, we can test predictive models and factors thought to impact this success as explanatory variables. Besides providing better answers to many research questions, predictive models can help inform managerial and policy decision-making. Managers face two key questions with respect to radical inventions: “how does one successfully promote one’s own radical invention?” and “how does one stop a competitor’s radical invention that threatens one’s market dominance?” Although policy makers face similar questions when working to support and protect key industries, they must also cope with complex resource allocation problems when deciding on funding for projects dealing with novel technology. Here the questions of interest are more general and may include such queries as “how likely is this radical invention to succeed?” and “what resources are needed in addition to research funds to help commercialize radical technology?”

In summary, a number of difficult issues will be far easier to resolve using the clearer definition of radical invention we have provided here. The two unique features of the operationalization of the definition will also prove useful: first, the ability to identify potential radical inventions before they hit the market; and second, the ability to investigate why some radical inventions will be successful while others will fail.

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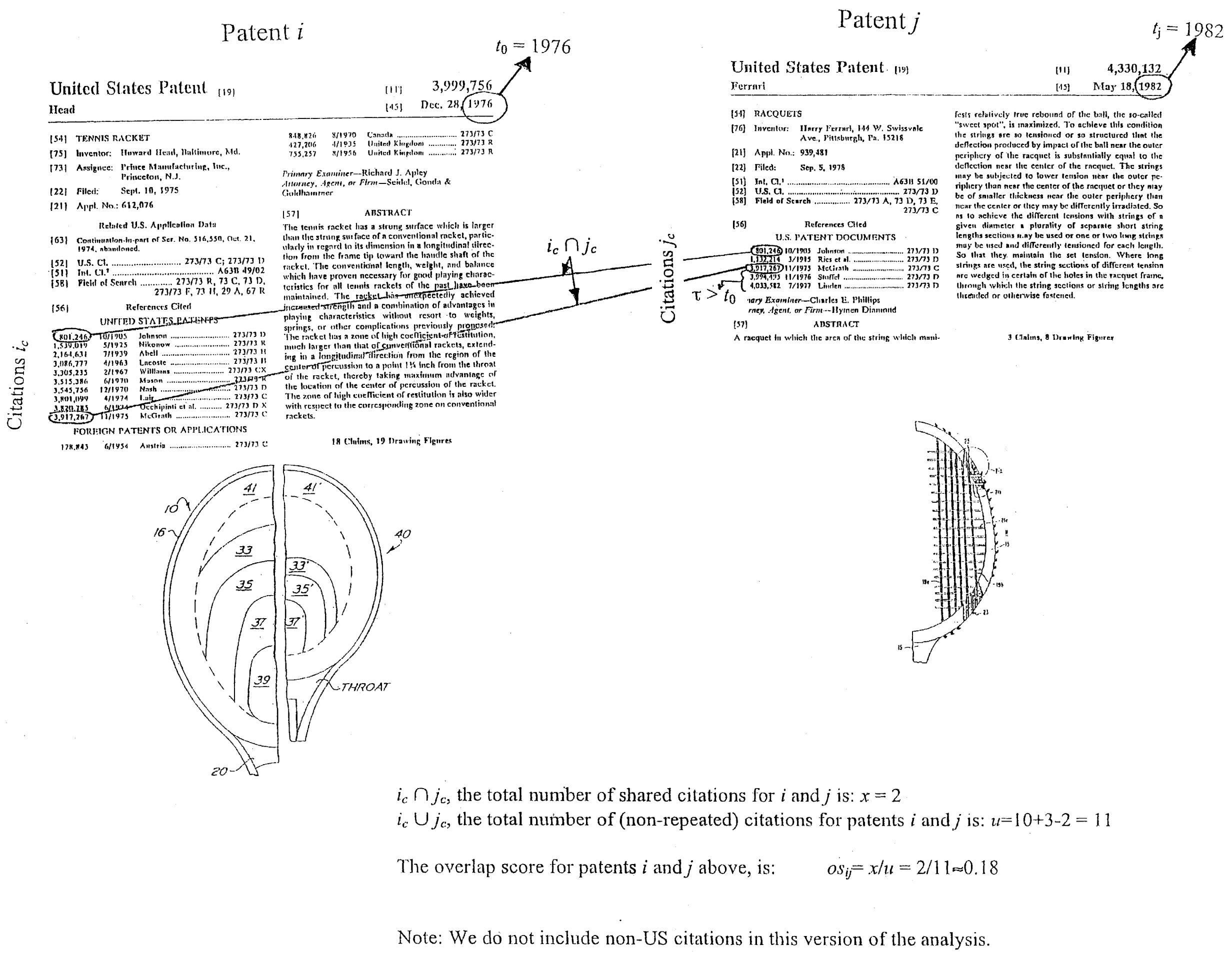
## Appendix A

Illustration of how to compute the overlap score between two patents *i* and *j*.

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