The Technology Cycle and Technology Transfer Strategies

Kenneth A. Zahringer, Christos Kolympiris, and Nicholas Kalaitzandonakes

Abstract University technology transfer offices (TTOs) must make decisions about whether and how to commercialize university innovations and do so with little or no information about the ultimate market value of the products that might eventually be derived from those innovations. Using technology life cycle theory, we derive and assess the usefulness of metrics that could provide additional information to assist in TTO decision making. We find that being able to locate a given innovation along a life cycle progression can decrease the uncertainty inherent in technology transfer decisions.

Introduction

University technology transfer offices (TTOs) face a daunting task. Acting as the agent both of the individual faculty member that produced a given invention and of the university as a whole, the TTO is responsible for assessing the potential value of a nascent, patented technology in final product markets. Based on that assessment, the TTO must then decide whether to commercialize the invention and what the optimal means, from the university's point of view, might be for doing so. This generally involves entering into some sort of agreement with a private firm to do the necessary follow-on research and development to turn the invention into a marketable product. Even under the best of conditions, the valuation process is largely a matter of entrepreneurial judgment; both the original inventors and their prospective firm partners find it difficult to arrive at an accurate estimate (Siegel et al. 2007). A primary reason for this difficulty is the high degree of uncertainty

K.A. Zahringer (✉) • N. Kalaitzandonakes
Department of Agricultural and Applied Economics, University of Missouri, Columbia, MO, USA
e-mail: ZahringerK@missouri.edu

C. Kolympiris
University of Bath, Bath, UK

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surrounding that value. New inventions often require considerable development to transform them into an innovative product. The relative costs and possible outcomes of alternative development paths are not clear at the outset. In addition, it is virtually impossible to foresee all possible applications, and thus formulate a realistic valuation, of a new invention at such an early stage. The closer a given invention is to basic research, the greater is the degree of uncertainty surrounding its potential value (Bercovitz and Feldman 2006). Since the bulk of university research involves basic science, TTOs must contend with a large amount of uncertainty in their decision making about structuring technology transfer agreements with private industry.

In this paper we propose a simple method for generating additional information that TTOs may find valuable and helpful in intellectual property (IP) valuation and refining their technology transfer strategy. By using some fairly simple, easily obtained patent data, it is possible to arrive at a reasonably accurate view of the current state of the life cycle of the technology area in which a particular invention resides. We propose that the indicators we develop here can capture information regarding how the value of an invention, as well as uncertainty about its value, is influenced by the developmental stage of the overall technology, as reflected in the technology life cycle (TLC) progression. Thus, placing a particular invention in its life cycle context can give a TTO valuable information as to its likely value and how accurate that valuation might be. We illustrate this process within the context of a technology that has been essential to the development of all of biotechnology, including agricultural, the polymerase chain reaction (PCR).

The importance of the TTO's task, and thus our contribution to its successful completion, goes far beyond the potential income to the university from any given transfer agreement. The interaction between a university and a private firm may begin with a specific, isolated transaction regarding technology transfer, but it often progresses beyond that to a long-term relationship that is highly beneficial to both parties. In addition to subsequent technology transfer, this relationship may take the form of firm-sponsored research at the university, students becoming a source of quality personnel for the firm, and the creation of additional spin-off firms. How the relationship develops, and its ultimate value to both parties, can be strongly influenced by the quality of the initial transactions (Bercovitz and Feldman 2006). It is thus critical that individual technology transfer agreements be viewed as valuable and equitable by both parties.

The rest of the paper proceeds as follows: in the next section, we give an overview of our current study, its position within the TLC literature, and why the TLC concept might be valuable in TTO decision making. In two subsequent sections we discuss the TLC literature and describe PCR technology. Following that, we report our data selection process, describe the dataset and relate our empirical findings. The final section concludes.

Overview

Innovative technologies evolve over time. They often follow a path by which their scope of usage and technological advancement proceed in distinct periods: an introduction stage is followed by a growth stage until maturity and eventual decline are reached (Taylor and Taylor 2012). This so-called technology life cycle (TLC) is generally difficult to describe analytically as the observable characteristics of technologies may not adequately capture the beginning and/or end of a stage. As a result, a large body of work has employed various indices based on patent documents and bibliometrics in an attempt to capture and, ultimately, measure the TLC for a number of innovative technologies (e.g., Kayal and Waters 1999; Chang et al. 2010; Huang and Yan 2011).

While most of the existing literature has focused on the description and measurement of the TLC of various technologies, we are more interested gaining a more generalized understanding of how key features of a new technology change over its life cycle. That is, we want to know whether and how (a) the value of the technology, (b) its complexity, (c) the speed it progresses within the intellectual property (IP) system, and (d) the pace of technological progress change as the technology moves from the introduction to the maturity phase. We do so by empirically mapping the TLC of a fundamental discovery in the life sciences, the PCR process, and examining the evolution of such features during the lifecycle of this technology.

Theoretically, we expect changes over the life cycle of any new technology. We build this expectation on the notion that the breakthroughs of most innovative technologies tend to happen early in the life cycle and the marginal contribution of subsequent developments is diminishing over time. If that proposition holds, we expect all the abovementioned features of a given technology to differ over the life cycle. For instance, we expect the more valuable and original forms of the technology in the early stages of the TLC.

Our case study is interesting for, among other reasons, its broad applicability in the life sciences. PCR was developed by scientists at Cetus Corp. in the early and mid-1980s. PCR is a method of rapidly producing large quantities of DNA from an initially small sample. The innovation that PCR became is now a standard piece of equipment in molecular biology laboratories and in a wide range of disciplines. By 2002 over 3% of all articles cited in PubMed referred to it (Bartlett and Stirling 2003). From a technical standpoint, as we explain in detail in the following section, PCR follows an identifiable life cycle with a long history which makes it a suitable template for studying changes in a TLC.

We use patent data as a primary input for our empirical analysis. A technology, any technology, is not merely a specific product. Rather, a technology is a set of knowledge and skills needed to produce, manipulate, and improve upon the design that is embodied in that tangible product (Lundquist 2003). The patent record provides a means of tracking the spread of the technological knowledge and the industry's response to it in the form of further related innovation. To implement the

analysis, then, we rely on patent data of the PCR technology sourced by commercial vendor Thomson Innovation. We have obtained data from 2414 US utility patents applied for from 1985 to 2008 and granted through 2012. These data allow us to identify the life cycle of the technology as well as to estimate how its value and other key features changed over time.

Our results show that the majority of the technology characteristics we study do change during the life cycle. For instance, individual innovations within a given technology are potentially much more valuable during the early stages of the life cycle when compared to later stages. Of course, this is also when the value is most uncertain. This study is strictly retrospective; we know that PCR became a tremendously successful innovation. Many other inventions did not turn out so well. We also see how the progression of the TLC reflects the valuation of the overall technology by the wider market. As the TLC progresses and market actors become more familiar with the technology, the potential value of any given new invention becomes less uncertain. Thus, information concerning the current state of a TLC could aid TTO decision making.

Technology Life Cycle Theory

Innovation is one of the more visible categories of human action. Economic actors are engaged in a more or less continuous process of seeking out and choosing means that they believe will achieve their desired ends (Mises 1998). As part of this process, actors develop new means that differ to varying degrees from what has gone before. Some of these inventions are substantially novel, representing what Ayres (1988) calls a technological discontinuity and the beginning of a technology cycle. In Ayres' model the discontinuity provides a means of overcoming a technological barrier and opens up new technological opportunities. Over time, knowledge of the discontinuity diffuses, and actors exploit the new opportunities with incremental improvements to the original innovation. Gradually, innovation in the new area experiences diminishing returns as opportunities are realized and new constraints become binding. At some point a new discontinuity solves these constraints and signals the end of the old technology cycle and the beginning of a new one.

While the foregoing outlines TLC conceptually, in practice the process can be considerably more complicated. Innovation is always characterized by a great deal of uncertainty as to its ultimate market acceptance and value. Different technology areas are often characterized by particular timeframes between early research and market impact. Biotechnology, the general area within which PCR falls, often develops radically new products for markets that have yet to exist. Often these products are regulated, which adds to development costs and increases the time needed to bring them to a marketable state. This is especially true for pharmaceutical inventions (DiMasi and Grabowski 2007; Kalaitzandonakes et al. 2007). Thus the impacts of such technologies may take some time to develop (Powell and Moris 2004). In fact, our results indicate that PCR followed this basic pattern. The constraints which

constitute barriers to innovation are not only technological but also economic and social and include raw material availability, production capabilities, and customer acceptance, among others (Kline and Rosenberg 1986). Ayres (1988) also emphasized that the barriers to innovation may not be located in the technology area where the invention originates.

In fact, the technology area that provides the context for our study, PCR technology, offers an example of this. The research that led directly to PCR (Mullis et al. 1986) was presaged by earlier work (Kleppe et al. 1971). This research was plagued by the same issue that hampered Mullis' initial attempts at implementing his idea – the lack of a polymerase enzyme that was not denatured and rendered inert by the high temperatures involved in the PCR process. It was only the discovery and isolation, in the intervening years, of a DNA polymerase from the thermophilic bacteria *Thermus aquaticus* (Chien et al. 1976), which came to be known as Taq polymerase, that enabled the research team to turn PCR from a laboratory invention into a useful innovation and a subsequent torrent of products (Saiki et al. 1988).

Thus, the technology life cycle is characterized not only by uncertainty but also by change. As the example suggests, each new discovery or innovation, whether a novel discontinuity or a small incremental improvement, changes the opportunities and incentives faced by subsequent innovators. It is these changes that lead to the changing character of innovations over the course of the life cycle. There are two basic, complementary theoretical perspectives for describing the changes that occur over a technology life cycle (Taylor and Taylor 2012).

Building on Ayres' concept of technological discontinuity, Anderson and Tushman (1990) put forth a three-stage model of the technology life cycle. The cycle begins with the introduction of a discontinuous innovation. During this introductory period, often characterized as the fuzzy front end of innovation, uncertainty is at a very high level. Not only is the innovating firm, as well as others in the industry, assessing the full potential of the innovation, but it is also bringing resources together to enable further development. Often this entails explaining and selling the concept to others, sometimes in order to secure outside investment funding. The firm's relative success in this effort can be a significant factor in determining the length of the introductory phase and whether the innovation progresses beyond it (Schoonmaker et al. 2012). If successful, the discontinuity engenders a period of ferment when many variations on and improvements of the original invention are generated. Out of this period of ferment comes a dominant design that becomes the industry standard. The emergence of a dominant design marks the boundary between the period of ferment and that of incremental change. Innovators continue to make incremental improvements to the dominant design until another discontinuity occurs and begins its own cycle. Anderson and Tushman (1990) construct a model whose predictions are validated with historical data from glass, cement, and minicomputer manufacturing technology. Among other results, they find that most new designs and most of the total performance improvement in the innovation occur during the period of ferment. Also, they found that a dominant design is more likely to appear in a regime of low appropriability of the rents that accrue to the innovation. Taylor and Taylor (2012) term this the "macro view" of the technology life cycle. They also

point out that this model implies a shift in emphasis from innovation concerning product design (product innovation) during the ferment period to innovation concerning producing the product more efficiently (process innovation) during the period of incremental improvement.

A somewhat more quantitative, yet complementary, perspective is represented by what Taylor and Taylor (2012) term the "S-curve view" of the life cycle. This model is more widely used than the macro view and with greater diversity in parameters. Here different measures of patents awarded, units sold, performance improvements, or other characteristics are usually plotted against time, resulting in S-shaped, logistic style curves. Generally, this type of curve represents the pace of change in some sense; in this lies the complementarity with the macro view. During the introduction period immediately following the discontinuity, the rate of innovation is slower as knowledge of the discontinuity begins to diffuse and others come to understand its implications. This corresponds to the flatter initial portion of the curve. During the period of ferment, the pace of change increases, corresponding to the steeper central portion. As the technological opportunities come to be more fully exploited, the cycle enters the period of incremental improvement, and the pace of change slows again, which corresponds to the later, again flatter portion of the curve. In this study we employ concepts from both models to better understand the changes in the character of innovations that take place over the course of the technology life cycle.

Polymerase Chain Reaction Technology

The technique of polymerase chain reaction (PCR), a method allowing rapid production of large quantities of DNA from a small sample, was developed by scientists at Cetus Corp. in the early and mid-1980s. The basic idea of PCR was conceived by Cetus scientist Kary Mullis in 1983, and Mullis and Cetus applied for the first patent on this invention in 1985. Ultimately, the invention earned Mullis the 1993 Nobel Prize in chemistry. Initially, however, few of his colleagues saw the potential of the idea (Mullis 1990). The first attempts at implementing the idea were inefficient and inaccurate. It took another few years of work, including the adaptation of a special enzyme (Taq polymerase) that was instrumental to the process, by a team of Cetus scientists to bring PCR largely into the form we see today (Rabinow 1996). The innovation that PCR became is now a standard piece of equipment in molecular biology laboratories in a wide range of disciplines; as already discussed, in 2002, over 3% of all articles cited in PubMed referred to PCR (Bartlett and Stirling 2003).

In the PCR process, the initial sample of DNA is heated, causing the two strands of the double helix to separate. Also in the solution with the DNA are smaller molecules made of nucleotides, the same building blocks from which DNA is made, called oligonucleotide primers or simply primers. These primers are constructed so as to bind with specific spots in the unraveled DNA. The solution contains two different primers which, when attached to the DNA strand, bracket the area to be replicated. After the solution cools a bit, a special enzyme called a polymerase (hence

the name) builds a complementary strand of DNA between the primers. The solution is again heated, again separating the DNA strands. The newly constructed DNA strands become patterns for new sequences, along with the original sample. Thus with each cycle the amount of the target DNA sequence in the sample doubles in a sort of chain reaction (hence the rest of the name). The amount of DNA produced is limited only by the amount of ingredients in the original solution. This exponential progression allowed the original PCR process to multiply a given DNA sample a billion-fold in a matter of a few hours. More recent advances in the process have cut this time to 30 minutes or less with some techniques and equipment (Wittwer 2001).

The basic concept of PCR is straightforward and has proven to be highly adaptable. The needs of the different areas of research and analysis which use PCR technology have given rise to a host of different techniques. These involve differences in, for example, temperatures used, timing, primer design, or catalysts included in the solution (Hayashi 1994). PCR's simplicity and adaptability have added two main features that have made it a particularly interesting technology to study. First, since the basic technology is so adaptable and thus so powerful, a dominant design emerged in an environment where theory would not necessarily have predicted. We commonly see dominant designs in realms of low appropriability, where innovations are more likely to remain in the public domain (Anderson and Tushman 1990). Biotechnology, however, is generally a high appropriability regime; patents play an important role in maintaining these firms' ability to safeguard the rewards from innovation (Ko 1992). In this type of environment, we would expect to see multiple competing proprietary designs, but here we do not. It is likely that the simplicity of PCR made it difficult to invent around. Second, the dominant design emerged very early in the life cycle. TLC theory predicts that the dominant design would emerge during the growth phase or period of ferment (Anderson and Tushman 1990). Yet, with the adaptation of Taq polymerase (Saiki et al. 1988), the basic structure of the technology and the standard complement of ingredients were essentially standardized less than 2 years after the original patent was granted and before any significant adoption of the innovation by the scientific community. Later innovations enhanced the speed and decreased the cost of the process and broadened its range of applications, as described above, but did not change its basic characteristics. All in all, these unique features of PCR make it an interesting and instructive context for technology life cycle research. In addition, PCR technology has a well-defined starting point (Mullis 1990; Rabinow 1996) and represents what could be termed a significant competence-destroying technological discontinuity (Anderson and Tushman 1990); nothing like it had been available before. In the terminology of Taylor and Taylor (2012), for the technology application of amplifying DNA samples, PCR is the only extant paradigm. For the most part, later developments have broadened the range of research areas using PCR rather than replacing older versions of the technology. Thus we do not have several generations of PCR technology complicating the development of the life cycle. This gives us an opportunity, in a fairly simple context, to see how the path of development progressed during the lifecycle of this technology.

Data and Variables

Data Selection and Description

For our empirical analysis, we used patent data. To source a relevant patent dataset, we proceeded in two parallel directions. The one direction involved the identification of all biotechnology patents[1] in which the term "polymerase chain reaction" was included either in the title or in the abstract of a patent. Out of the total 155,985 biotechnology patents granted through 2012, 2059 included the term in question. The second direction was to directly identify the basic group of PCR patents awarded to Cetus Corp. (Carroll and Casimir 2003). The original PCR patent was heavily cited, garnering well over 3000 citations from follow-on patents. Under the premise that (some) citing patents may also represent PCR technologies, we included all patents that cited the original PCR patent as long as they were assigned the same primary four-digit IPC code. Removing patents already selected during the first direction we described above, we identified 434 additional patents, bringing the total dataset to 2493 PCR patents. As a final adjustment, we eliminated patents applied for after 2008. Given that the current median pendency time at the USPTO is in excess of 3 years (Mitra-Kahn et al. 2013), including issued patents applied for after 2008 would likely result in a sample selection bias toward short pendency patents at the end of the sample period. The final dataset includes 2414 US utility patents applied for 1985–2008 that meet our search criteria. All patents and features of the technology we are interested in were sourced from Thomson Innovation.

Study Design

To map the progression of the technology over the life cycle, we follow convention and chart the numbers of patents over time. Figure 1 shows the numbers of granted patents, grouped by the year each respective application was filed. Given the generally long time it takes for a patent application to be granted, we use the application date rather than publication date under the premise that it should better capture the time that the innovation was created. In order to smooth the curve and chart the underlying trends more clearly, we also include the 3-year moving average of the number of annual applications. The graph shows that PCR technology had an introductory period of approximately 8 years during which there were comparatively few patents filed each year. The growth phase lasted until 2002, after which the number of annual applications dropped dramatically, signaling entry into the

[1] To identify biotechnology patents, we employed the list of International Patent Classification (IPC) codes that belong to biotechnology compiled by OECD (2014). The IPC categories were A01H(1/00, 4/00), A61K(38/00, 39/00, 48/00), C02F3/34, C07G(11/00,13/00,15/00), C07K (4/00, 14/00, 16/00, 17/00, 19/00), C12M, C12N, C12P, C12Q, C12S, G01 N27/327, and G01 N33/ (53*, 54*, 55*, 57*, 68, 74, 76, 78, 88, 92).

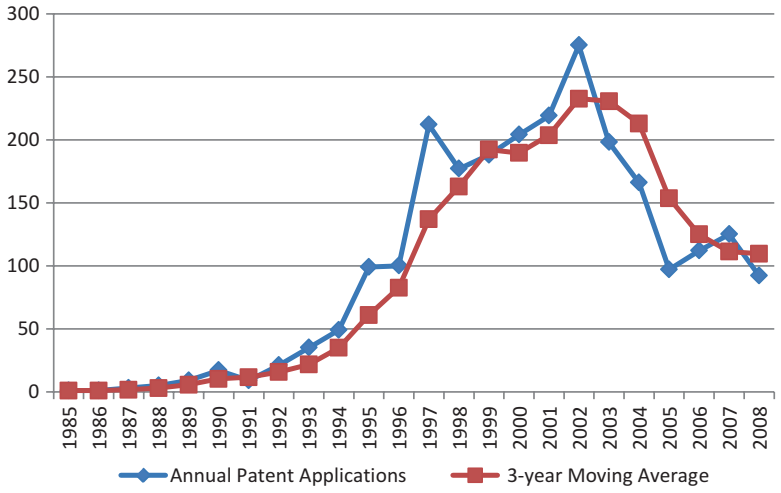

Fig. 1 Annual PCR-related patent applications

maturity phase. It appears that the innovation rate may have leveled off in the last 3 or 4 years of our sample. Thus we have the full spectrum of a technology life cycle in this sample, with each of the three phases represented.

As noted above, once we map the life cycle of the technology, we are interested in studying if and how key features of the technology change across time. The first feature we examine is the value of the technology which we approximate with patent value. We measure patent value with the number of times a given patent has been cited by later patents (forward citations) and with the size of the group of patents that describe a given technology (patent family). We use these measures based on evidence that they correlate with the market value of a technology as well as with importance, impact, and other measures of value (Harhoff et al. 2003; Gambardella et al. 2008; Sneed and Johnson 2009; Fischer and Leidinger 2014; Odasso et al. 2015).

The second feature we analyze is patent pendency, defined as the length of time that elapses between the application date of a given patent and its grant date. Patent pendency can be influenced by a host of factors including the strategic behavior of applicants which may favor long or short pendency time (Lanjouw and Schankerman 2004; Berger et al. 2012), patent value (Régibeau and Rockett 2010), work load at the patent office (Harhoff and Wagner 2009), familiarity of the patent examiner with the technology (Lemley and Sampat 2012), and so on. All these factors may drive patent pendency in different ways, and here we are interested to see the final outcome of the interplay of these factors over time.

The third feature we analyze is the pace of technological change. Following previous works (Kayal 1999; Kayal and Waters 1999; Haupt et al. 2007), we employ the technology cycle time (TCT) index to measure technological change. TCT is defined as the average age of the patents cited by the focal patent, and it is calculated

as the elapsed time (in months) between the publication dates[2] of the two patents. Once the elapsed time is measured for all the patents in questions, we calculate TCT by averaging out the figures for all patents. Formally, TCT is defined as $\mathrm{TCT}_{\mathrm{f}} = n^{-1}\sum_{r=0}^{n}\frac{\left(p_{\mathrm{f}} - p_{\mathrm{r}}\right)}{30}$ for each focal patent f, where n is the number of prior art patents referenced by the focal patent, p_{f} is the publication date of the focal patent, and p_{r} is the publication date of the referenced patent. To be clear, the shorter the cycle time, the smaller the index and the faster the pace of technological advancement.

The fourth feature we study is the originality of the technology. To measure originality we follow Harhoff and Wagner (2009) in constructing the originality measure first pioneered by Trajtenberg et al. (1997). This index measures the degree of commonality between the technology area of the focal patent and those of the patents it references as prior art. The rationale is that more fundamental patents will draw on a wider technological base than those that are more incremental improvements. Patents that reference patents from many different technology areas earn a higher score on this index, while those that draw on only a few areas earn lower scores. This index is a Herfindahl-type measure that measures the degree of similarity between the technology area of the focal patent and the technology areas of the patents referenced as prior art. Formally, the measure is calculated as $ORIGINAL_i = 1 - \sum_{N_k}^{k=1}\left(\frac{Refs_{ik}}{Refs_i}\right)^2$, where patent i references patents from k technology classes. Thus $Refs_i$ is the total number of referenced patents for focal patent i, and $Refs_{ik}$ is the number of referenced patents from focal patent i that fall into technology class k. Importantly, N_k is the total number of technology areas represented in the list of referenced patents, not the total number of technology areas in the classification system.[3] To calculate this index, we first converted the primary IPC code of the focal patent and all of its referenced patents to the ISI-OST-INPI classification system, which more accurately reflects technological relatedness than does the IPC coding system (Schmoch 2008).[4] Each term in the summation, then, is the number of patent references belonging to a particular technology class divided by the total number of patent references for the focal patent. The index ranges from 0 for the least original patents to 1 for the most original patents.

[2] Application dates could capture elapsed time more accurately. However, the vast majority of applications do not include any prior art when they are originally submitted; these are commonly provided later in a document known as an Information Disclosure Statement (IDS) (USPTO 2015). Accordingly, this limits the use of application dates.

[3] The index assigns a score of 0 for any patent without any or with only 1 reference included as previous art. As a result, the first patents, which have no antecedents, would receive a score of 0. This is not consistent with the theoretical expectation that the first patents are also among the most original. As such, any patent with no references was assigned an originality score of 1. For patents with 1 reference, if the patent and its reference were of the same technology class, the patent scored 0. If they were of different classes, the patent scored 1.

[4] This classification scheme collapses a total of 550 unique four-digit IPC codes into 35 technology classes.

The fifth feature we study is the complexity of the technology. We measure complexity via patent scope (Van Zeebroeck 2007), defined as the number of different four-digit IPC codes assigned to a patent during the examination process (Lerner 1994; Gans et al. 2008). The main rationale behind that measure is that more complex technologies span across multiple field boundaries. IPCs indicate the industrial field(s) a patent belongs to and as such the higher the number of IPC codes for a patent, the greater the complexity.

Results

Technology Value

Figure 2 plots the average values of forward citations and patent family size for each year of the technology cycle. Both values are at their maximum during the introduction phase before declining and maintaining a relatively constant level during growth and maturity. The outlier year of 2001 in the family size plot is due to one large family, with over 2000 members, consisting of patents related to a particular area of cancer diagnosis and therapy. Seven members of this family, having to do with PCR techniques, are included in our dataset. In this technology cycle, then, high value patents are very strongly clustered in the introductory phase, consistent with previous evidence (Haupt et al. 2007; Régibeau and Rockett 2010). This is an important observation in that it suggests that, when dealing with very new inventions, TTOs should position the university to be able to benefit strongly from a highly valuable invention. However, this is also when the value is most uncertain,

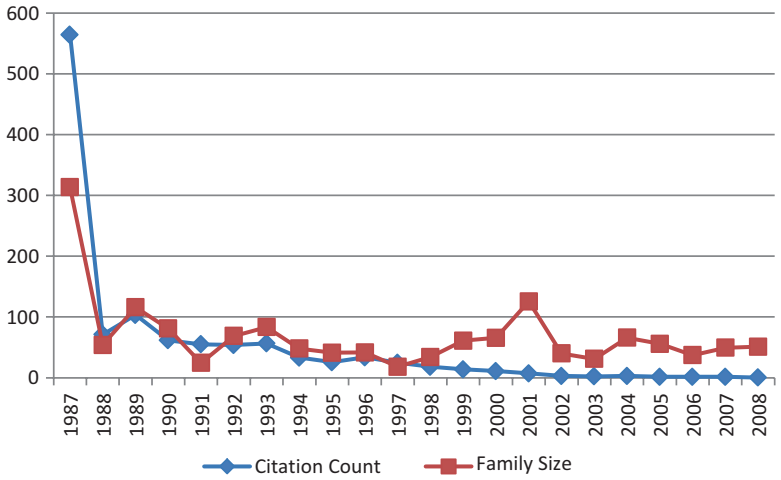

Fig. 2 Average annual patent value

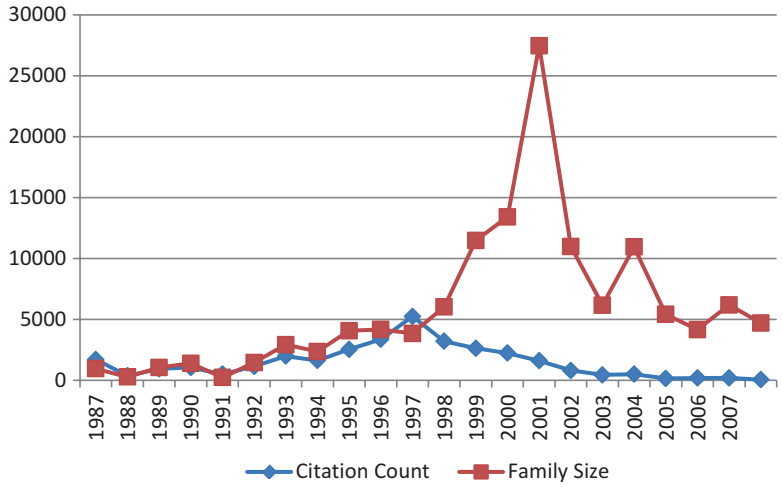

Fig. 3 Annual total patent value

and it is the potential licensee firm that bears most of that uncertainty. Its R&D investment in the invention could come to naught. Thus, in order to make a technology transfer agreement attractive to the firm, the university may need to be willing to share some portion of the uncertainty and the associated risk of low or no return on the invention.

Also relevant to questions of value are predictions that most of the improvements in quality and performance, and by extension added value, of a given technology will occur during the growth phase (Kline and Rosenberg 1986; Anderson and Tushman 1990). As a rough approximation of this, we summed each of our value measures for each year. As Fig. 3 shows, both forward citations and family size peak during the growth phase, although in different years. Citations peak in 1997, during the early portion of the growth phase, while family size is at its maximum in the latter part, in 2001. Although the height of the family size peak is affected by the outlier discussed above, the location of the peak is consistent with surrounding years. The increase in annual patent applications and grants that signals the beginning of the growth phase, then, is an indication that the wider technology community has decided that development of the technology is worth pursuing. Thus the level of uncertainty about the value of a given follow-on invention is reduced, along with the risk of that invention being of extremely low value. By the time the maturity phase is reached, and the annual flow of patents begins to taper off, there is even more market data available that further reduces the uncertainty of the valuation of a particular new invention in the technology field. We see that the probability of both extremes of value, very high and very low, is much lower than in the introductory phase of the TLC.

Patent Pendency

Figure 4 depicts the average pendency time of the PCR patents in the life cycle. In line with Haupt et al. (2007), the figure reveals a roughly inversely U-shaped relationship: pendency times increase during the early phases, it then decreases with a minimum value of 30 months, and then it increases again until it eventually flattens out. While there is a wealth of literature on patent pendency (Popp et al. 2004; Batabyal and Nijkamp 2008; Harhoff and Wagner 2009; Henkel and Jell 2010; Van Zeebroeck 2011; Xie and Giles 2011), only Haupt et al. (2007) and Régibeau and Rockett (2010) study pendency in the life cycle. The two studies reach slightly different conclusions with regard to how pendency might change over time. Still, they both provide explanations of pendency revolving around patent complexity and learning at the patent office.[5] A major issue is that these explanations find it difficult to account for the short pendency of the earliest patents, an observation that holds in our sample. Even beyond the scope of our work, a possible explanation for that trend is that because novelty and nonobviousness are patentability requirements, it may be straightforward to recognize a highly original invention even if the patent examiner does not fully understand the technology at the time. That understanding may become more important later on, when more patent applications related to the

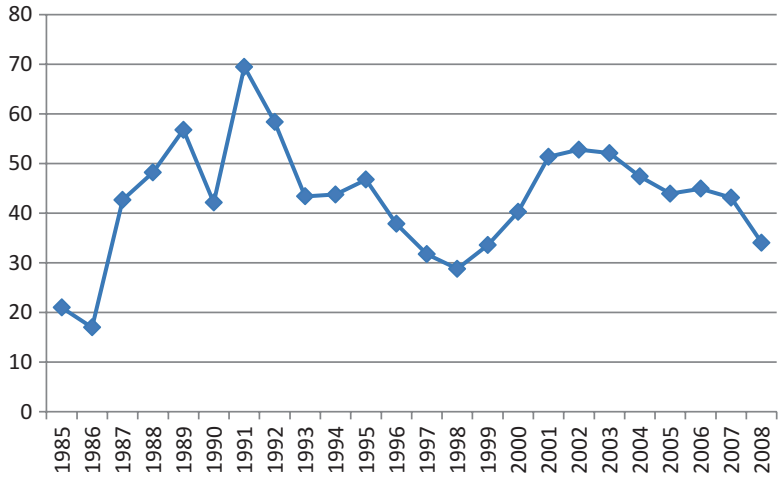

Fig. 4 Average patent pendency in months

[5] Régibeau and Rockett (2010) expected that pendency time would steadily decrease throughout the technology cycle, due to decreasing technological uncertainty in the examination process as the patent office learned more about the new technology. Their results were generally consistent with this expectation. Haupt et al. (2007), on the other hand, expected pendency time to decrease during the growth phase due to learning at the patent office, but then to extend again during the maturity phase since "then the applications have to be compared to a higher technological standard" (p. 393).

new technology are filed. At this point finer judgments would have to be made, and the learning curve at the patent office would become a more important factor.

Pace of Technological Change

Figure 5 plots the TCT over time and it documents that it varies over the technology cycle. TCT is higher (the cycle is longer and the technology progresses more slowly) during the early and later stages, but the pace, as expected, increases during the growth phase. Interestingly, this U-shaped pattern is strikingly similar to that of pendency time in Fig. 4. It therefore implies that pendency and the pace of technological change move together. It is likely that when technology advances faster, the actions of applicants promote speedier patent process times, and/or the patent office responds in the same manner. These two indicators can give additional information as to the current state of the TLC. Since the TTO will be examining the TLC in real time, as it were, comparing TCT with the flow of applications and grants may allow a more accurate judgment regarding the TLC stage and its impact on patent value.

Complexity

In Fig. 6 we see that patent scope, our measure of complexity, does not vary in any regular fashion over the course of the technology life cycle; the slope of the trend line is essentially zero. This, then, is one area that the TTO may be able to safely

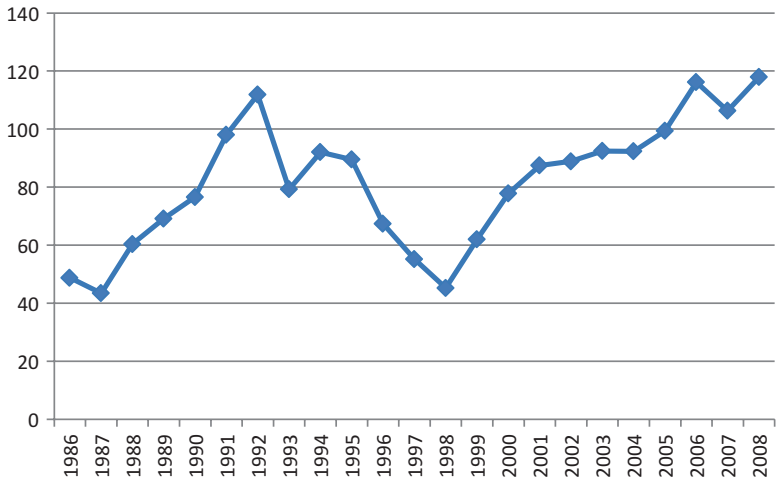

Fig. 5 Technology cycle time

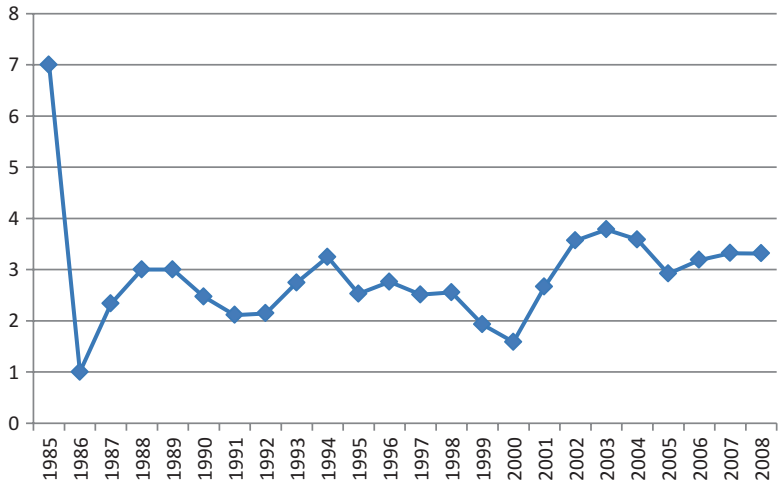

Fig. 6 Average patent scope

ignore in its valuation decision. More complex inventions are not necessarily any more or less valuable; other factors are more important.

Conclusion

One fundamental purpose of a university TTO is to maximize the future income streams from university IP holdings. In order to do this successfully, the TTO must estimate the market value of a patented invention as accurately as possible and formulate a technology transfer agreement with a private firm to develop the invention into a marketable innovation. This is a difficult task, always undertaken in conditions of uncertainty and insufficient information. In this study we have proposed that indicators drawn from patent data, specifically the annual flow of granted patents and TCT, can be used to position a given invention within the context of a progressing technology life cycle. Using the real-world example of PCR, we demonstrated that these indicators vary predictably over the TLC and thus are potentially useful in charting the current state of a specific life cycle. Further, we have shown how these indicators relate to the potential value of a patented invention and the uncertainty of that value. These indicators can be calculated from readily available patent data and can inform TTO decisions about the optimal form for a particular technology transfer agreement.

More specifically, our results shed some light on the relative merits of equity holdings versus traditional licensing as remuneration to the university for technology transfer. Under conditions of high uncertainty, as pertain early in a TLC, by accepting an equity stake in the firm, the university bears some of the uncertainty surrounding a new invention, making the agreement more attractive to the firm,

which may be a relatively new startup with limited resources. At the same time, equity may be more attractive to the university as its fortunes are tied to overall firm performance rather than the potential of just one invention (Feldman et al. 2002). Late in the TLC, when the prospective value of an invention is both more moderate and more certain, a traditional licensing agreement may be more effective in maximizing university income and maintaining the relationship with the private firm.

We must also keep in mind that income stream maximization is not the only goal for university TTOs. In some cases it may not even be the primary goal, taking a back seat to the mission of ensuring research results are used to benefit society at large (OECD 2003). This is often especially true in agriculture, as the founding principles of land grant universities include a mandate to share the results of agricultural research through their cooperative extension services. Even in these cases, though, the TTO may be in a position of allocating scarce resources to numerous technology transfer projects, as described by Cartalos in another chapter in this volume, and would need to assess their relative values to society in order to ensure the best use of TTO capabilities. Our results here might be helpful in decreasing the uncertainty surrounding the potential value of these types of agricultural innovations and thus promote economically optimal TTO decisions.

This is admittedly a preliminary investigation. While our results agree in large part with previous work in this area (e.g., Kayal and Waters 1999; Haupt et al. 2007), more research using other technology areas is definitely needed in order to demonstrate the general applicability of the concepts advanced here.

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