A Stochastic Life Cycle Model of Academic Research and Patent Licensing

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Abstract

We extend the literature on life cycle behavior of faculty researchers by assuming two knowledge stocks, scientific (free to all) and patentable (appropriable). Faculty derive utility from research effort, leisure, prestige in knowledge accumulation, and income. Faculty with a strong preference for one type of research tend to devote more time to it, but if the knowledge stock associated with it grows fast enough, then they reallocate time from more or less preferred research later in the life cycle. Both knowledge stocks matter to utility, so if one grows sufficiently larger, the marginal utility from an increase in the other becomes greater, implying this time reallocation. An increase in license income, such as from the Bayh-Dole Act, increases in time in applied research, but faculty do this by decreasing their time in leisure first, then their time in basic research. Thus, the scientific knowledge stock is not always smaller as a result of this type of legislation. The primary effect of spillovers of the Pasteur's Quadrant type is to increase the scientific knowledge stock, but faculty effort in basic research need not decrease, and may increase.

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1 Introduction

The growth of licensing of university research in the last thirty years has been accompanied by some controversy. Some are concerned that this increased focus on research projects with more apparent commercial potential has had adverse effects on basic research in universities (Boyd *et al.*, 2003; Zerhouni, 2004; Rae-Dupree, 2008; Washburn, 2008). However, empirical tests have found limited, if any, effects (Thursby *et al.*, 2007; Thursby and Thursby, 2011). It has also been argued that the distinction between basic and applied research has become blurred in the sense that "basic" scientific advances have arisen from "applied" research (e.g., research in Pasteur's Quadrant, Stokes 1997).

We develop a life-cycle model of faculty behavior that allow us to examine some of these issues. Specifically, we consider a faculty researcher/inventor who allocates her time between applied research, basic research, and leisure. We define basic research as that effort primarily intended to increase the stock of scientific knowledge (which is freely available to all), applied research as that effort primarily intended to increase the stock of patentable knowledge (which is appropriable). We use the term "primarily" to highlight the fact that we allow spillovers between both types of research. Success in basic research can result in increases in the stock of patentable knowledge, and success in applied research can result in increases in the stock of scientific knowledge. However, knowledge accumulation is stochastic. Increased effort in research merely increases the probability of an increase in the stocks of knowledge. We assume the researcher derives utility from research effort *per se* as well as the prestige from success and income. Prestige from success is measured by her stocks of both scientific and patentable knowledge. Her university salary depends on both knowledge stocks, but her license income depends only on her patentable knowledge stock.

Because it is impossible to derive many unambiguous results from our general stochastic life-cycle model, we adopt specific functional forms and simulate the outcome. We conduct 500 runs in each case and graph the averages in order to obtain a depiction of the expected outcomes. For all of the analyses, we consider nine benchmark cases depending on the preferences and productivities of the faculty researcher/inventor. These correspond to those faculty who have a strong preference for applied research, a strong preference for basic research, and are indifferent between them, and to those who are more productive in applied research, more productive in basic research, or are equally productive. To consider the effect of the Bayh-Dole Act, we consider her behavior with and without the possibility of licensing. We also consider her behavior with and without the effect of Pasteur's Quadrant.

The time paths of applied research, basic research, and leisure over the life cycle are much as anticipated. The one prominent result for all cases is that time in leisure increases steadily throughout the entire life cycle. Next, faculty with a strong preference for one type of research devote more time to it than either the other type of research or leisure throughout the entire life cycle. As a result, the knowledge stock associated with the more preferred type of research grows faster. However, roughly midway through the life cycle, she begins to reallocate her time from the more preferred research to the less preferred. Because both stocks of knowledge matter to her utility, through both prestige and university salary, once one of these stocks reaches a sufficiently higher level, the marginal utility from an increase the other stock becomes greater, implying a reallocation of effort from more to less preferred research during this latter period. This provides one explanation for why even superstars in basic research tend to work on more applied problems later in their careers.

Those who are indifferent between each type of research tend to allocate their time in research based on their productivity. If she is more productive in applied research, then she devotes more time to it than to basic research and leisure. Conversely, the more productive she is in basic research, then she devotes more time to it than to applied research and leisure. One rather interesting result is that for the equally productive as well as indifferent researcher, time in applied research is essentially constant over the life cycle, while time in basic research decreases. In the latter two cases, it seems that these faculty consume as much basic research as possible early in their careers, but the lure of license income after retirement induces them to devote more and more time to applied research as time in their careers runs out.

The effects of the Bayh-Dole Act on the allocation of time are interesting. We compare the outcome with and without license income for our benchmark cases. In all cases, faculty respond to an increase in license income by increasing the time they spend in applied research, in the range of one to five percent, and decreasing the time they spend in both basic research and leisure throughout the entire life cycle. Moreover, in every case, the reduction in leisure stays rather constant over the entire life cycle at about two percent, so time in basic research decreases only when the increase in time in applied research surpasses two percent. That is, researchers seem to increase time in applied research by first decreasing their time in leisure, then basic research. The reduction in time spent in basic research is the greatest (in percentage terms) for those with a strong preference for it. The magnitudes of these changes, however, vary with the researcher's productivity. They are largest for those faculty who are more productive in applied research, and smallest for those who are more productive in basic research. These results are contrary to those of Thursby, Thursby, and Gupta-Mukherjee (2007). In their model, the increase in time in applied research due to the Bayh-Dole Act comes solely at the expense of time in leisure, not basic research.

The effects of the Bayh-Dole Act on the knowledge stocks are surprising. Although the patentable knowledge stock is greater throughout the entire life cycle in all cases, as expected, the scientific knowledge stock is not always smaller. It is smaller for those with a strong preference for basic research, whatever their productivity, with magnitudes in the two to six percent range. The changes in the scientific stock are negligible for those who are indifferent between applied and basic research. Finally, the scientific stock is also greater toward the end of the life cycle for those who both have a strong preference for and are more productive at applied research. The increased growth in the patentable knowledge stock leads these faculty to reallocate some of their time back from applied to basic research because the marginal utility from the scientific knowledge stock is greater.

Finally, the effects of research of the Pasteur's Quadrant type are examined by comparing the outcomes when there are spillovers between both types of research and when there are only spillovers from basic to applied research. When we move from the traditional "linear" R&D model with only spillovers from basic to applied research to a model where spillovers from applied to basic research are also important, the primary first-order effect is that applied research becomes more productive by contributing, in expectation, to the growth of both knowledge stocks. This generally results in a reallocation of time from basic to applied research. However, because research is stochastic, this increase in productivity is merely a small increase in the probability of success, so the resulting changes in time allocation are very small, usually less than one percent and always less than two percent. Nevertheless, allowing spillovers from applied to basic research does result in increases in the stock of scientific knowledge throughout the entire life cycle, even if these increases are not large in percentage terms.

In Section 2, we discuss the related literature. Section 3 presents the general model, and Section 4 presents simulation results for several parametrizations of an explicit model. Section 5 provides some concluding remarks.

2 Literature Review

The analysis herein is related to the theoretical literature on both the economics of science and university-industry technology transfer. While most of the literature on the economics of science examines faculty research, these studies abstract from both licensing and spillovers between applied and basic research. And although much of the literature on technology transfer focuses on faculty incentives, the choice between basic research and applied research (or development), and licensing, these studies generally abstract from life-cycle effects.[1]

Stephan (1996) emphasizes that scientists attach importance to solving research problems, especially to being the first to solve them (Hagstrom, 1965; Kuhn, 1970; Merton, 1957). Levin and Stephan (1991) embed this behavior into a life-cycle model in which scientists choose how to allocate effort between research

[1] See, for example, Aghion, Dewatripont, and Stein (2005), Beath, et al. (2003), Belenzon and Schankerman (2009), Jensen and Thursby (2001, 2004), Jensen, Thursby, and Thursby (2003, 2010), and Lach and Schankerman (2008).

and income-earning activities. Stern's (2004) empirical analysis of wages offered to Ph.D. biologists provides evidence that professors are willing to pay to do research of their own choosing. Dasgupta and David (1987, 1994) examine reward systems in which all rewards go to the winner of the "race" to be first to discover a result. Thursby, Thursby and Gupta-Mukherjee (2007) extend the Levin and Stephan model to analyze the effects of license revenue from faculty research and tenure.

The studies by Levin and Stephan (LS), Thursby, Thursby, and Gupta-Mukherjee (TTG), and Jensen and Thursby (JT) are most relevant. In their models, scientists engage in research for two reasons: their love of puzzle solving and an investment in future earnings. In LS, faculty earn a university salary that is positively related to the portion of time spent teaching and the stock of publications at each date. In TTG and JT, researchers accumulate knowledge in their time spent working that contributes to both utility and income. They also allow researchers to do either (or both) basic and applied research. When their research has an applied component, faculty earn license income. Our life cycle model is similar in that faculty can do both basic and applied research, derive utility from both types of research, and accumulate knowledge that impacts future utility and financial rewards. We differ from TTG in that, as in JT, there are two knowledge stocks, scientific and patentable, and the faculty member's university salary depends upon both stocks. We differ from both TTG and JT in that we assume both research processes are uncertain, so knowledge accumulation is stochastic. We also differ from TTG in that we do not consider tenure, but we do consider differing tastes for and abilities to do each type of research and differences in spillovers between each type of research. In contrast to JT, we do not have a university administration selecting the faculty salary and teaching load to maximize it's own utility, which depends on the quality of education.

Empirical evidence on commercialization of university inventions and the nature of faculty research shows varying results. Cohen *et al.*'s (1998) study of university-industry research centers shows commercial outputs of research increase and publications decrease (except in biotechnology). Given the importance of publications for industrial productivity (Adams, 1990), these results may be some cause for concern. However, Rosenberg and Nelson (1994) discuss a long history of relationships in industrial and university research, and Murray's (2002) interviews with academic scientists in tissue engineering indicate basic scientific and technical solutions can go hand-in-hand in some industries. Mansfield's study of 321 academic researchers found that faculty frequently worked on basic problems suggested by their industrial consulting. Similarly, Zucker *et al.* (1994, 1998) found that the most productive scientists in biotechnology often start new enterprises while continuing research in their academic appointments. These are examples of spillovers from applied to basic research popularly known by the term Pasteur's Quadrant. Our analysis provides direct tests of this phenomenon and its effects.

There is little theoretical research on the financial incentives facing faculty and the allocation of effort across types of research. Beath *et al.* (2003) and JT both examine faculty research incentives in a principal agent context where the university is the principal and the faculty member the agent. Beath *et al.*'s analysis is static and examines the potential for the university to ease its budget constraint by allowing faculty to conduct applied research on a consulting basis. In contrast, JT's model is dynamic and provides an analysis of the effect of patent licensing on research and the quality of education, where the latter effect is a function of research choices (and hence future stocks of knowledge) as well as the portion of patentable knowledge that can be used in education. Given their emphasis on the education problem, they abstract from life cycle patterns.

3 Model

We consider the research efforts, knowledge stocks, and income of a faculty member over her life cycle. At each date t, she allocates her time between applied research a_t, basic research b_t, and leisure l_t, where we index time so that $a_t + b_t + l_t = 1$. We define applied research as that primarily intended to increase the stock of patentable knowledge A_t, and basic research as that primarily intended to increase the stock of scientific knowledge B_t. At each date she also earns income in current academic salary $S(A_t, B_t)$ and, possibly, in license revenue from her patentable knowledge $R(A_t)$. We depart from prior studies, which generally do not assume her salary depends on her patentable knowledge. We also assume that her academic salary depends on her current stocks of both scientific and patentable knowledge, because there is evidence that patents do matter in some academic settings, and there is growing evidence that they may matter more in the future.[2] Our approach differs from previous life-cycle studies of faculty research by focusing on both patentable and scientific knowledge stocks and assuming both types of research are stochastic.

3.1 Preferences

Faculty have preferences that depend on research effort itself, leisure, the prestige resulting from successful research, and income. Specifically, at each date, $U_F = U_F(a_t, b_t, A_t, B_t, l_t, Y_t)$. As noted above, we assume utility depends on research effort *per se*, based upon evidence that researchers who do basic research may have a taste for it (Stern 1999). We extend this notion to a taste for applied research as well, as in JT. Our faculty researcher gains utility from her efforts to solve the problem (Hagstrom (1965, p. 16)) and the prestige of her successes in research (Stephan 1996). We use the knowledge stocks as measures of this prestige, so that past success in either basic or applied research generates additional current and future

[2] Five years ago the Texas A&M University System Board of Regents voted to allow consideration of faculty members' patents and commercialization of their research in deciding whether to grant them tenure (Lipka 2006).

utility, independently of whether it generates additional income. Her income at t is

$$Y_t = \phi R(A_t) + S(A_t, B_t) \tag{1}$$

where ϕ is her share of the license revenue from her patentable knowledge stock. Throughout the rest of the paper, we assume her utility is quasi-linear

$$U_F = U(a_t, b_t, A_t, B_t, l_t) + \phi R(A_t) + S(A_t, B_t) \tag{2}$$

where U is strictly quasi-concave in (a_t, b_t, l_t). Naturally we assume no license revenue without patentable knowledge, $R_t(0) = 0$. Note that research does not increase the stock of knowledge until the next period, so current effort affects current utility and future income and prestige, but not current income or prestige.

3.2 Production

In period t, the allocation of time between applied and basic research and the current knowledge stocks determine the probability of success in each research program. These probabilistic production functions for knowledge are the transition probabilities between current state (A, B) and potential future states (A', B') where $A' \geqslant A$ and $B' \geqslant B$. Thus, for given efforts and knowledge stocks (a, b, A, B), denote the probability that the state transitions to $(A'$,$B')$ by $P(A', B'|a, b, A, B)$. Notice this form allows for spillovers in both directions between basic and applied research. That is, we allow spillovers from basic to applied research and from applied to basic research (Pasteur's quadrant, Mansfield 1995 and Stokes 1997). Naturally we assume these are increasing in the efforts and knowledge stocks, and strictly quasi-concave in (a, b).

3.3 Value Function

We consider a problem of T periods, where the faculty retires at T. For notational convenience, set $\theta_t = (a_t, b_t, l_t, A_t, B_t)$.Then for any time period t where $t \neq T$, her value function is defined recursively by

$$\begin{aligned} V_t(A_t, B_t) \quad = \quad & \max_{(a_t, b_t)} U(a_t, b_t, A_t, B_t, l_t) + \phi R(A_t) + S(A_t, B_t) \\ & + \beta \sum_{A_{t+1}} \sum_{B_{t+1}} P(A_{t+1}, B_{t+1}|\theta_t) V_{t+1}(A_{t+1}, B_{t+1}) \end{aligned} \tag{3}$$

subject to $a_t > 0$, $b_t > 0$, and $l_t = 1 - a_t - b_t$, and

$$V_{T+1}(A_T, B_T) =$$

$$\frac{1-\beta^p}{1-\beta}\sum_{A_{T+1}}\sum_{B_{T+1}}P(A_{T+1},B_{T+1}|\Phi_T)[U(0,0,A_{T+1},B_{T+1},1)+\phi R(A_{T+1})] \tag{4}$$

where p denotes the number of years over which the final stock applied knowledge A_{T+1} continues to provide income after retirement.

4 Simulations of an Explicit Model

Given the inherent difficulties in determining general properties of the general value function for this problem[3], we develop an explicit version of the model which we can then use to simulate expected solutions to the faculty researcher's life-cycle optimization problem in (3).

4.1 Functional Forms

First, we assume that the subutility function U is additively separable in research effort, leisure, and prestige, or $U(a_t, b_t, A_t, B_t, l_t) = a^{\gamma_a}b^{\gamma_b} + l^{1-\gamma_a-\gamma_b} + A^{\gamma_a}B^{\gamma_b}$, where $\gamma_a$and γ_b are positive constants such that $\gamma_a + \gamma_b < 1$. The research effort and prestige components take Cobb-Douglas form, which allows us to use γ_a (γ_b) as a measure of the researcher's preference for applied (basic) research and patentable (scientific) knowledge. We assume her license income is linear in the stock of patentable knowledge and her university salary is Cobb-Douglas in both knowledge stocks, $R(A) = A$ and $S(A, B) = A^sB^{1-s}$, where $s \in (0, 1)$ is a constant. Generally expect her stock of scientific knowledge to have a greater impact on her salary, $s < 1/2$. These assumptions guarantee that her preferences are characterized by positive but diminishing marginal utility in her time spent in each type of research, time in leisure, and her stock of each type of knowledge. Thus, her utility function takes the form

$$U_F(a_t, b_t, A_t, B_t, l_t) = a_t^{\gamma_a}b_t^{\gamma_b} + l_t^{1-\gamma_a-\gamma_b} + A_t^{\gamma_a}B_t^{\gamma_b} + \phi A_t + A_t^sB_t^{1-s}. \tag{5}$$

For tractability, we assume that the state space for each knowledge stock is countably finite, so $A, B = 1, 2, ...M$. We also assume the transition probabilities for each type of knowledge stock are independent and take the forms

$$P(A+1|a,A,B) = \frac{(\delta_a + \Delta_{AA}A + \Delta_{BA}B)a}{1 + (\delta_a + \Delta_{AA} + \Delta_{BA}B)a} \tag{6a}$$

and

$$P(B+1|b,A,B) = \frac{(\delta_b + \Delta_{AB}A + \Delta_{BB}B)b}{1 + (\delta_b + \Delta_{AB}A + \Delta_{BB}B)b} \tag{6b}$$

[3] Deriving definite results is difficult even when knowledge accummulation is certain. See the large number of ambiguous rsults in JT.

where δ_a, δ_b, Δ_{AA}, Δ_{BA}, Δ_{AB}, and Δ_{BB} are positive constants. The expression in (6a) indicates that the probability of success in achieving the next one-step increase in patentable knowledge is an increasing function of the current effort in applied research and both current knowledge stocks. The parameter δ_a measures the strength of the direct effect of time in applied research on this probability of success. The parameter Δ_{AA} indexes the effect of the current stock of patentable knowledge on this probability of success, while the parameter Δ_{BA} indexes the effect the current stock of scientific knowledge on this probability. Generally we expect the own effect to be greater, or $\Delta_{AA} > \Delta_{BA}$. Also note from (6$a$) that current effort in basic research does not have an effect on the probability of success in increasing patentable knowledge. However, past effort in basic research does have an effect on this probability to the extent that it succeeded in increasing the stock of scientific knowledge. The interpretations of the parameters δ_b, Δ_{AB}, and Δ_{AB} in the transition probability in (6b) are analogous, though it is worth emphasizing that Δ_{AB} also represents the strength of a Pasteur's Quadrant type of effect. That is, if $\Delta_{AB} = 0$, then neither applied research nor the stock of patentable knowledge have any spillover effect on basic research. However, if $\Delta_{AB} > 0$, then greater (past) success in applied research increases the probability of success in current basic research.

4.2 Simulation

We simulate a researcher's life over $T = 30$ time periods using the equilibrium solution obtained in the model. The equilibrium solution consists of two functions $a_t^*(A, B)$ and $b_t^*(A, B)$ that satisfy the first order conditions for (3) given the explicit forms above. In each period, we first substitute the applied and basic effort solutions and the knowledge stocks from the previous period into the transition functions $(6a, b)$ in order to compute the transition probability of each pair of stocks in the current period. We then form a spectrum from 0 to 1, the length of whose segments correspond to the probabilities that we have just calculated. Next, we draw a random number from a uniform distribution on $[0, 1]$. The segment on the spectrum to which the drawn number belongs determines the realization of (A, B) for the present period. Having found (A, B) and knowing t, we simply look into the equilibrium for the realizations of applied and basic efforts.

In period $t = 1$, we assume that the researcher starts at the minimum levels of both applied and basic knowledge $(1, 1)$ and apply the preceding steps to find the time paths of $a_t^*(A, B)$ and $b_t^*(A, B)$ until the last period T. Our results also include the progressions of applied and basic knowledge, salary income, and rent generated from patentable knowledge. In order to mitigate the effects of extreme draws and obtain results that closely approximate the equilibrium paths, we run the simulation 500 times for each variable and report the time paths of the averages in the following.

4.3 Results

We examine several cases of interest, depending upon the faculty member's preferences and abilities for each type of research, whether she earns license revenue, and whether there are spillovers from applied to basic research. Regarding preferences, we assume she can either have a strong preference for applied research and patentable knowledge, ($\gamma_a = .6$, $\gamma_b = .2$), a strong preference for basic research and scientific knowledge ($\gamma_a = .2$, $\gamma_b = .6$), or be indifferent between them ($\gamma_a = .4$, $\gamma_b = .4$). In each of these cases, her preference for either type of research is at least as great as her preference for leisure. Similarly, we consider cases where she can be more productive (in expectation) in applied research ($\delta_a = .06$, $\delta_b = .03$), more productive in basic research ($\delta_a = .03$, $\delta_b = .06$), or equally productive ($\delta_a = .05$, $\delta_b = .05$). This yields nine basic cases. We consider the effects of the Bayh-Dole Act for each of these nine cases by examining the differences in research efforts and leisure with and without license income ($\phi = .3$, $\phi = 0$). We finally consider the effects of Pasteur's Quadrant by setting own effects of $\Delta_{AA} = \Delta_{BB} = .5$ and examining the differences with and without spillovers between applied and basic research ($\Delta_{AB} = .1$, $\Delta_{AB} = 0$). In all cases, we set the maximum stocks at $M = 10$, interest rate at .05 ($\beta = .95$), $s = .4$, and $p = 10$.

4.3.1 General Life Cycle Properties

First consider the trends of research efforts, leisure, and knowledge stocks over the life cycle. Figure 1a shows the expected time paths of applied effort, basic effort, and leisure, and Figure 1b shows the expected time paths of scientific and patentable knowledge for each of the nine basic cases. We assume there are spillovers in each direction, but the researcher earns no license income, in all cases. Although time is discrete ($t = 1, ..., 30$), we graph these values as continuous to show the trends more clearly. In each figure, the upper row corresponds to a researcher with a strong preference for applied research, the middle row to one who is indifferent between applied and basic research, and the bottom row to one who prefers basic research. Similarly, the left column corresponds to a researcher who is more productive in applied research, the middle column to one who is equally productive in applied and basic research, and the right column to one who is more productive in basic research. For each diagram in Figure 1a, time in applied research is the solid line, time in basic research is the dashed line, and time in leisure is the dotted line. For each diagram in Figure 1b, the solid line is the stock of patentable knowledge and the dashed line is the stock of scientific knowledge.

First consider the allocation of effort over time. As is apparent, the results are quite robust to differences in preference and productivity. The most persistent result, in general, is that time in leisure increases steadily throughout the entire life cycle. This is consistent, of course, with well-known results that faculty research productivity decreases over the life cycle (Oster and Hammermesh 1998). It is also worthwhile to highlight that the time path of leisure remains unchanged across different productivity types. The absence of a difference indicates that leisure merely subtracts from total research time, and has no direct influence on the probability of success in either type of research. Thus, a change in productivity only results in reallocation in research efforts.

Moreover, Figure 1a shows a dominant effect of preferences on time allocation. The researcher spends unambiguously more time in her preferred type of research than anything else. For example, as seen in the upper row, if she has a strong preference for applied research, then she devotes more time to it than to either basic research or leisure throughout the entire life cycle. Nevertheless, productivity does have an impact on time allocation. Interestingly, if she is both high productive in applied research and has a strong preference for it, her effort in applied research effort decreases halfway through the life cycle, as seen in the upper left diagram. More effort is spent on basic research while leisure remains unchanged during this latter part of the life cycle. To understand this, refer to the corresponding diagram in Figure 1b, where the stock of patentable knowledge grows faster and higher. Because the stock of scientific knowledge matters to her utility, through both prestige and university salary, it is important that she ensure its growth as well. As a result, once the patentable stock reaches a sufficiently higher level, the marginal utility from an increase her scientific stock becomes greater, implying a reallocation of effort from applied to basic research during this latter period. Once the scientific stock has grown enough, the preference effect returns and restores previous levels of applied effort until the end of the life cycle. However, if she has strong preference for applied research but is equally productive in each type of research (the upper middle diagram), then the time she reallocates from applied to basic research midway though the life cycle is not as great, because she is more productive in basic research. Finally, if she has a strong preference for applied research but is highly productive in basic research (the upper right diagram), then the time path of applied research is relatively constant, because no reallocation of effort is needed for the growth of stock of scientific knowledge to keep pace with that of the stock of patentable knowledge.

Similarly, if the researcher has a strong preference for basic research, then she devotes more time to it than to either applied research or leisure throughout the entire life cycle. Note that the greatest initial level of effort in basic research occurs if she is also highly productive in basic research (see the lower right diagram). However, about midway in her life cycle, she gradually reallocates time from basic to applied research, in response to the incentive to increase her prestige and income by increasing the stock of patentable knowledge. Eventually, however, she returns to higher levels of basic research after the stock of patentable knowledge has grown sufficiently. In sum, the same patterns apply to researchers who have a strong preference for basic research, except in a reverse order.

As expected, if she is indifferent between applied and basic research, her allocation of time between them depends on her productivity. Before analyzing the diagrams in the middle row of Figure 1a, however, it is important to note that if she has the same taste for each type of research, then time in basic research plays a relatively more important role in her utility because of its contribution to her salary. Even with spillovers in research, time in basic research is more likely to increase the stock of scientific knowledge, and the magnitude of this stock has a greater impact on her salary than the stock of patentable knowledge ($s < 1/2$). Therefore, we see a general trend of prominence in basic research in all three diagrams, especially the two on the left. The differences in particular time paths are, of course, attributed to productivity differences. In the first and second diagrams, where the researcher is more (or no less) productive in applied research, she can spend less time in applied research and focus more on basic research while still achieving the same expectation of success. Conversely, if she is more productive in basic research, as in the lower right diagram, then she devotes more time to it than to applied research or leisure early in her career. That is, she starts her career by focusing on her comparative advantage. Subsequently, because her salary also depends on the stock of patentable knowledge, she reallocates time from basic to applied research throughout the life cycle to compensate for her low productivity in applied research. Eventually, time in applied research overtakes that in basic research.

In Figure 1b, the accumulation of either knowledge stock is most rapid for those faculty with both a strong preference and high productivity in that particular area (top left and bottom right). These are perhaps the classic examples of those fortunate individuals who love to do what they are good at. The growth rate of a stock declines when either the related preference or productivity diminishes. From the left to the right in any row, as productivity in applied research decreases and productivity in basic research increases, the time trend (slope) of the scientific knowledge stock increases while that of the patentable knowledge stock decreases. Similarly, from the top to the bottom in any column, as preference for applied research decreases and preference for basic research increases, again the time trend of the scientific knowledge stock increases while that of the patentable knowledge stock decreases. Despite the difference in growth rates, these processes are very smooth for all researches, evidencing the adjustments in time allocation noted above.

We have shown that a researcher's preferences between each type of research tend to determine the growth of each knowledge stock and the levels of research efforts over time. On the other hand, the effect of her productivity is more apparent in the pattern of her allocation of time between each type of research over the life cycle. If a researcher's type of productivity and preference coincide, then she is most willing to venture into her relatively less productive research realm in the middle of her career, although the absolute level of this type of research remains lower than that of her preferred type. The reason she allocates time to her relatively less productive research is that her utility depends on each knowledge stock, through prestige and income, but is subject to diminishing returns. Thus,if either stock grows significantly larger, then the marginal increase in utility from an increase in the smaller knowledge stock exceeds that from an increase in the larger stock. As noted above, this gives the researcher an incentive to reallocate her time to the type of research most likely to increase the smaller stock. Loosely speaking, regardless of a strong preference for and a strong productivity in a particular type of research, for the sake of her prestige and salary she needs to maintain both stocks at reasonable levels.

4.3.2 The Bayh-Dole Effect

Next consider the effects of the Bayh-Dole Act on the variables of interest. These results are depicted in Figures 2a and 2b, a set of diagrams corresponding to each of the nine basic cases, organized as in Figures 1a and 1b. We again assume spillovers in each direction, and graph these differences as continuous to show the trends clearly. In each diagram, we plot the difference between a choice variable or stock when license income can be earned ($\phi = .2$) and that when there is no license income ($\phi = 0$). Thus, a positive (negative) value for a variable indicates that passage of the Bayh-Dole Act resulted in an increase (decrease) in that variable. As before, in the diagrams of Figure 2a, the difference in time in applied research (basic research, leisure) is the solid (dashed, dotted) line, and in the diagrams of Figure 2b, the difference in the stock of patentable (scientific) knowledge is the solid (dashed) line. Again, the results are quite robust to differences in preferences and productivity.

Figure 2a shows the effects of the introduction of (or increase in) license income such as that created by the Bayh-Dole Act. Recalling that we index the researcher's total time per period to equal 1, these diagrams show increases in time spent in applied research in the range of 1% to 5%, and decreases in time spent in basic research and leisure in the range of 1% to 5%. An increase in license income increases the contribution of her stock of patentable knowledge to her utility, thus giving her an incentive to increase time spent in the type of research more likely to increase that stock. This reallocation is greatest at the beginning of a researcher's career. Notice that in nearly every case, this increase in applied research comes at the expense of both leisure and basic research. Moreover, in every case, the reduction in leisure stays rather constant over the entire life cycle at about 2%, so time in basic research decreases only when the increase in time spent in applied research surpasses 2%. Nevertheless, the reduction in time spent in basic research often exceeds that in leisure. This is generally due to our assumption that, *ceteris paribus*, the marginal utility of leisure is less than that of either type of research.[4]

Those with a strong preference for applied research (upper row) respond to an increase in license income by increasing time spent in applied research at the expense of time spent in both basic research and leisure,

[4] Recall $1 - \gamma_a + \gamma_b \leq \min\{\gamma_a, \gamma_b\}$ and $1 - \gamma_a + \gamma_b < \max\{\gamma_a, \gamma_b\}$ in all of our simulations. Separabilty of utility in research and leisure matters as well, but primarily in the constancy of the reduction in leisure over time, not its magnitude.

throughout the entire life cycle. However, the reduction in time in basic research is generally less than that in leisure, and decreases to zero at the very end of the life cycle.

However, those faculty with a strong preference for basic research (bottom row) respond to an increase in license income by increasing time spent in applied research, and decreasing time spent in both basic research and leisure, throughout the entire life cycle. Moreover, in this case the reduction in time in basic research exceeds that in leisure for the entire life cycle. The magnitudes of these changes, however, do vary with the productivity of the researcher. They are largest for the case of those who are more productive in applied research (left column), when the increase in applied research and decrease in basic research are about 1% to 5% for most of the life cycle. They are smallest for the case of those who are more productive in basic research (right column), when the increase in applied research and decrease in basic research are in the range of 1% to 2%.

Finally, faculty who are indifferent between applied and basic research also respond to an increase in license income by increasing the time they spend in applied research, and decreasing the time they spend in both basic research and leisure, throughout the entire life cycle. The reduction in time spent in basic research is greater than that in leisure at the beginning of the life cycle, but not the end.

These results are noteworthy because they differ from those in TTG. In their model, the increased time in applied research comes solely at the expense of time in leisure, not basic research. The fact that our results differ must arise from differences in the assumptions on knowledge "production" in the two models. Specifically, we assume there are two different knowledge stocks, rather than one, and that both types of research can contribute to both knowledge stocks, though at differential rates. In addition, while both stocks influence the researcher's prestige and salary, only the stock of patentable knowledge can influence her license income. In TTG, the only stock of knowledge influences both her salary and her license income.

Next, notice in Figure 2b that, as expected, there is an increase in the stock of patentable knowledge in almost all cases. The most prominent change is in the case where a researcher strongly prefers basic research but has an productivity advantage in applied research. Apparently, she is the type of researcher that benefits the most from Bayh-Dole. On the one hand, a researcher with a similar preference but with a low productivity in applied research does not gain as much from the introduction of license income (bottom right). As a result, the magnitude of the change is increasing in productivity in applied research from the right to the left in the bottom row. On the other hand, an applied researcher with an aptitude for it already spends a lot of time in this field, thus does not gain as much (top left). Naturally, as productivity in applied research decreases from the left to the right in the first row, the increase in the patentable knowledge stock becomes smaller.

Given the concern that the increased focus on applied research due to the Bayh-Dole Act has adversely impacted basic research, and the fact that time in basic research decreases in nearly all cases, it is interesting that the stock of scientific knowledge does not always decrease. In one case, researchers who prefer and are more productive in applied research (the upper left diagram), the scientific knowledge stock is actually greater throughout the life cycle. And in other cases, the changes in the scientific stock are negligible (e.g., faculty indifferent between applied and basic research, the middle row). The most noticeable decreases occur for faculty who have a strong preference for basic research (the bottom row), which is expected because these faculty also react to Bayh-Dole with the largest decreases in time spent in basic research. However, the size of these decreases is small in percentage terms. Recall from the bottom row of Figure 1b that the maximum size of the scientific knowledge stock in these cases ranges (left to right) from roughly 7 to 9, so the decreases due to Bayh-Dole are roughly 5% to 2%. These magnitudes vary somewhat with different parametric choices, but were generally quite robust. For context, note that the increase in the scientific knowledge stock for the case noted above is roughly 6%. Faculty who like and are more productive in applied research tend to reallocate time from leisure to both types of research, thereby increasing both knowledge stocks.

4.3.3 The Pasteur's Quadrant Effect

Finally, we want to examine the effects of the increased importance of research of the Pasteur's Quadrant type in which there are spillovers from applied research to basic research (as well as from basic to applied research). These results are shown in Figures 3a and 3b, with nine diagrams again corresponding to each of the nine basic cases, organized as before. In each diagram, we plot the difference between the variable when there are spillovers in both directions and when there are spillovers only from basic to applied research. Precisely, in the first case the stock of scientific knowledge has a positive impact on the probability of success in applied research, and the stock of patentable knowledge has a positive impact on the probability of success in basic research ($\Delta_{BA} > 0$, $\Delta_{AB} > 0$). In the second case, however, the stock of scientific knowledge has a positive impact on the probability of success in applied research, but the stock of patentable knowledge no impact on the probability of success in basic research ($\Delta_{BA} > 0$, $\Delta_{AB} = 0$). Thus, a positive (negative) value for a variable indicates that the presence of a Pasteur's Quadrant effect results in an increase (decrease) in that variable. Again, in Figure 3a, the difference in time in applied research (basic research, leisure) is the solid (dashed, dotted) line, and in Figure 3b, the difference in the stock of patentable (scientific) knowledge is the solid (dashed) line.

Although these graphs are not as smooth as those in the preceding figures (despite averaging over 500 simulations), the results are clear and intuitive. Perhaps most noteworthy is the fact that the resulting changes in the choice variables are small, usually less than 1% and always less than 2%, as shown in Figure

3a. Again these magnitudes vary somewhat with different parametric choices, but they are generally quite robust. It is not surprising that they are generally small. After all, the first-order effect of introducing Pasteur's Quadrant spillovers is merely a marginal increase in the probability of success in increasing the stock of scientific knowledge. This is most obvious for time in leisure, which generally does not change, and changes very little when it does. Next, with two exceptions discussed below, introduction of Pasteur's Quadrant spillovers results in a reallocation of time from basic to applied research. This is not surprising, because this effect allows some reallocation to occur without an adverse effect on the expected growth of the stock of scientific knowledge. Nevertheless, this reallocation is small and essentially vanishes toward the end of the life cycle.

The exceptions occur for researchers who are more productive in applied research, and either prefer applied research or are indifferent between it and basic research (the top two diagrams in the left column). Reallocation of time from basic to applied research results in more rapid growth of the stock of patentable knowledge. In fact, this outpaces the growth of scientific knowledge sufficiently that the researcher soon has an incentive to reallocate her time from applied research back to basic research. As noted above, the reason she returns to her relatively less productive research is that her utility depends on both knowledge stocks, but the marginal utility of each is diminishing. Thus, when her patentable knowledge stock grows significantly larger, the marginal utility from prestige and income from an increase in her scientific knowledge stock exceeds that from a further increase in the patentable stock, which creates an incentive to reallocate time from applied to basic research. This effect is most pronounced for a researcher who both prefers and is more productive in applied research (the upper left diagram). The initial reallocation of time into applied research is the greatest in this case, and patentable knowledge is expected to grow so fast that she has an incentive to reduce the magnitude of this reallocation immediately. Then, less than one-third of the way into the life cycle, the marginal utility from increases in the scientific knowledge stock becomes large enough that she reverses course and reallocates time from applied to basic research for the remainder of her life cycle. It is also noteworthy that this is the only case in which time in leisure decreases throughout the entire life cycle (although the decrease is small). That is, those who like applied research and are good at it also respond to a Pasteur's Quadrant effect by increasing total time in research at the expense of leisure.

Finally, the introduction of a Pasteur's Quadrant effect results in changes in the time paths of the knowledge stocks that are generally small as well (often close to zero, and always less than 2.5% of the maximum size of the stocks). Again, introducing spillovers from applied to basic research merely results in a marginal increase in the probability of success in increasing the scientific knowledge stock. Nevertheless, as seen in Figure 3b, this does result in a larger stock of scientific knowledge throughout the entire life cycle, even if the increases are small in percentage terms. Thus, at least in our model, these spillovers do not have a detrimental effect of the growth of scientific knowledge. In fact, as an additional source of productivity in the production of scientific knowledge, in expectation they result in greater stocks of this knowledge.

5 Concluding Remarks

We have considered the decision of a faculty inventor/researcher of how to allocate her time between basic research, applied research, and leisure throughout the life-cycle in a model with two types of knowledge stocks, scientific and patentable. The time paths of applied research, basic research, and leisure over the life cycle are much as anticipated, given the preceding literature. That is, time in leisure increases steadily throughout the entire life cycle, and faculty with a strong preference for one type of research devote more time to it than either the other type of research or leisure throughout the entire life cycle. As a result, the knowledge stock associated with the more preferred type of research grows faster. However, because we assume two types of knowledge, we find some new results. For example, roughly midway through the life cycle, she begins to reallocate her time from the more preferred research to the less preferred. The reason is that both stocks of knowledge matter to her utility, through both prestige and university salary. Once one of these stocks reaches a sufficiently higher level, the marginal utility from an increase the other stock becomes greater, implying a reallocation of effort from more to less preferred research during this latter period.

Introduction of a Bayh-Dole Act induces faculty to increase the time they spend in applied research at the expense of both basic research and leisure, although time in basic research decreases only when the increase in time in applied research surpasses two percent. The reduction in time spent in basic research is the greatest (in percentage terms) for those with a strong preference for it, and for those who are more productive in applied research. Although the patentable knowledge stock is greater throughout the entire life cycle, as expected, the scientific knowledge stock is not always smaller. It is greater toward the end of the life cycle for those who both have a strong preference for and are more productive at applied research. This is another case where the assumption of two knowledge stocks leads to new results. The increased growth in the patentable knowledge stock leads these faculty to reallocate some of their time back from applied to basic research because the marginal utility from the scientific knowledge stock is greater.

Finally, the effects of spillovers the Pasteur's Quadrant type are largely as expected, though small. This generally results in a reallocation of time from basic to applied research, but the spillover from applied to basic research implies increases in the stock of scientific knowledge as well as patentable knowledge throughout the entire life cycle, even if these increases are not large in percentage terms. There is one case in which this time reallocation does not occur for the entire life cycle. Faculty who both prefer and are more productive in applied research initially reallocate the most time into applied research, so patentable knowledge grows so fast that she has an incentive to reduce the magnitude of this reallocation immediately. Then, less than one-third of the way into the life cycle, the marginal utility from increases in the scientific knowledge stock becomes large enough that she reverses course and reallocates time from applied to basic research for the remainder of her life cycle. Again, this result occurs only because there are two knowledge stocks that contribute to the researcher's utility.

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Figure 1a: Time Allocation throughout the Life Cycle

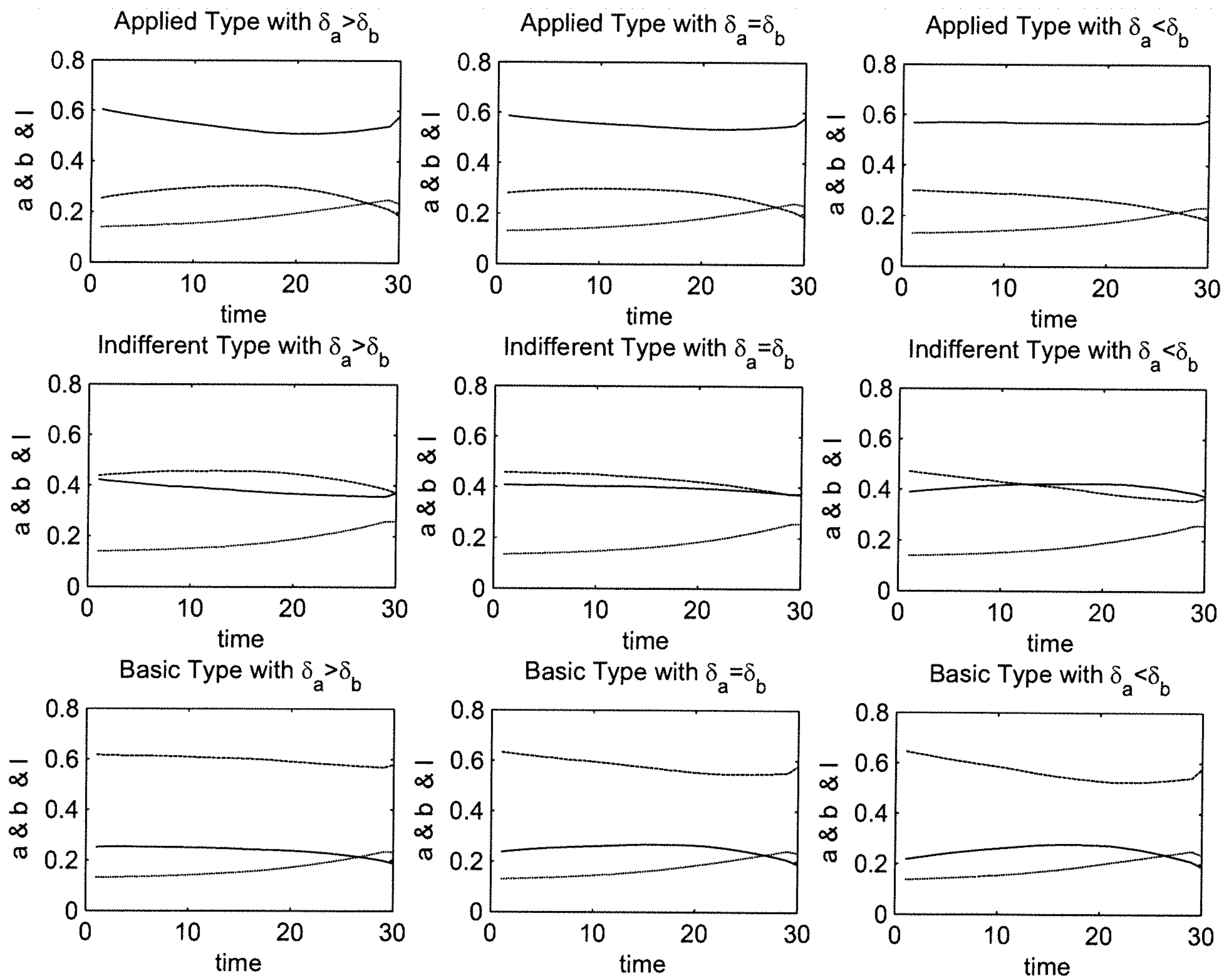

Figure 1b: Growth of Knowledge Stocks throughout the Life Cycle

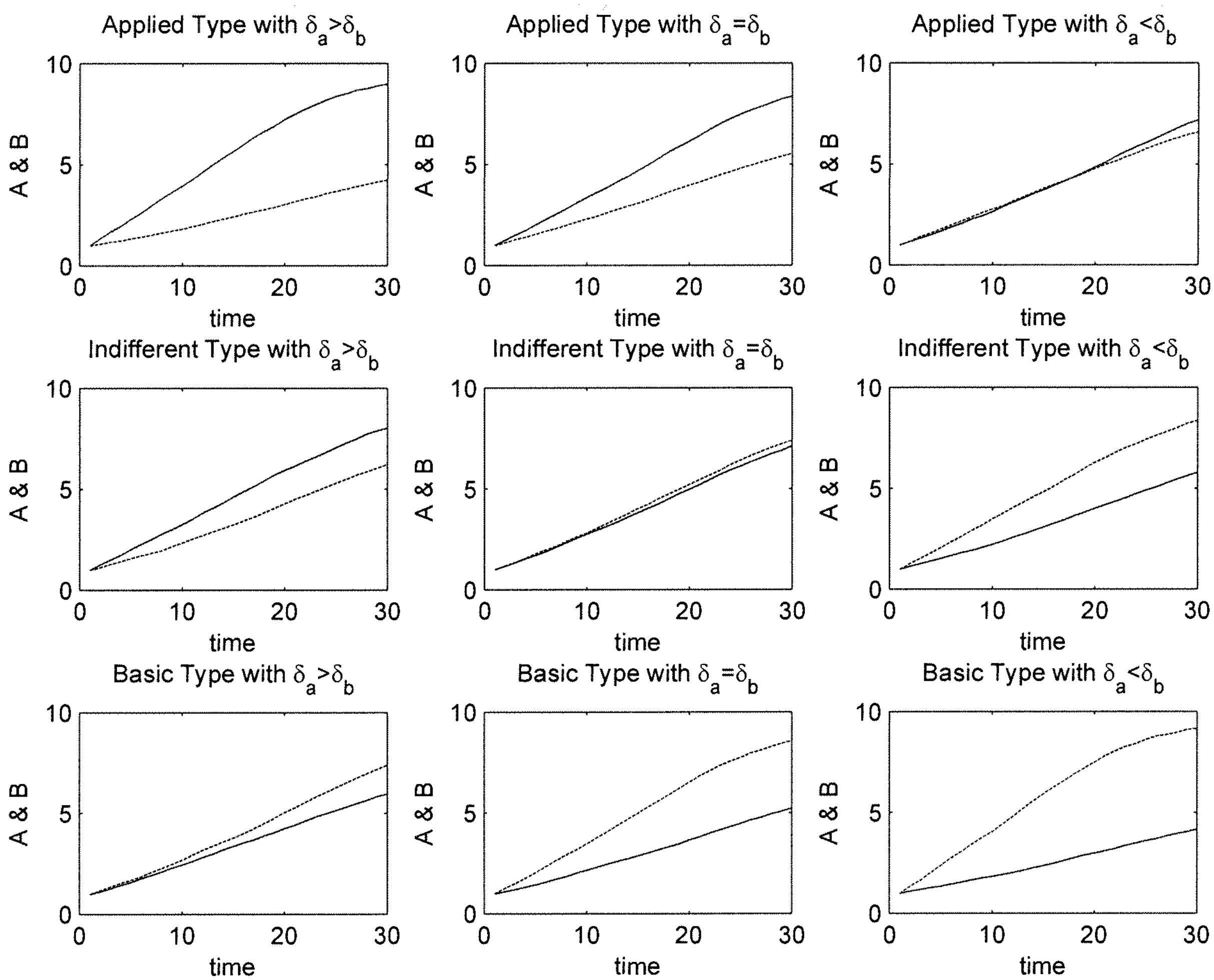

Figure 2a: Changes in Time Allocation due to Bayh-Dole Act

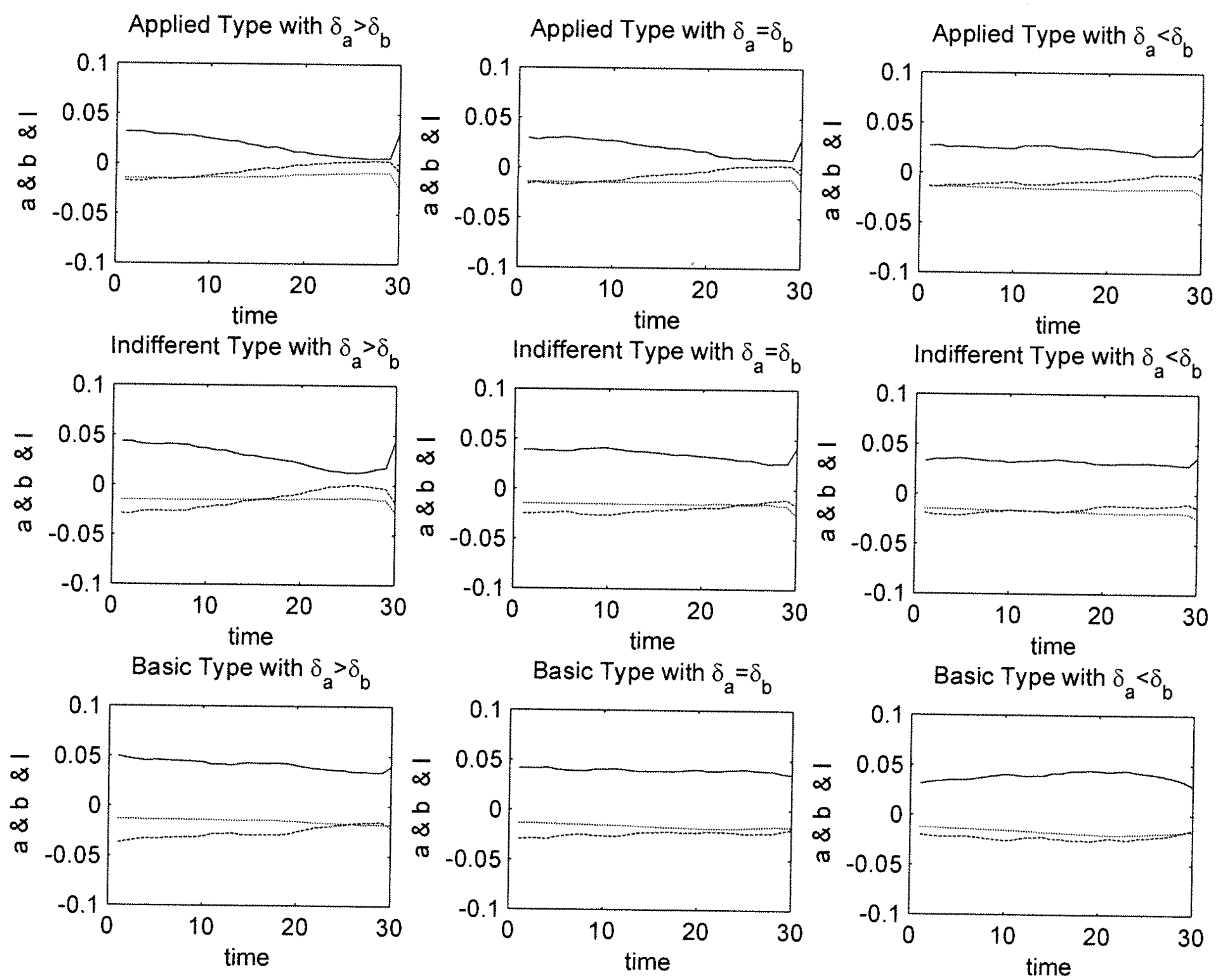

Figure 2b: Changes in Knowledge Stocks due to Bayh-Dole Act

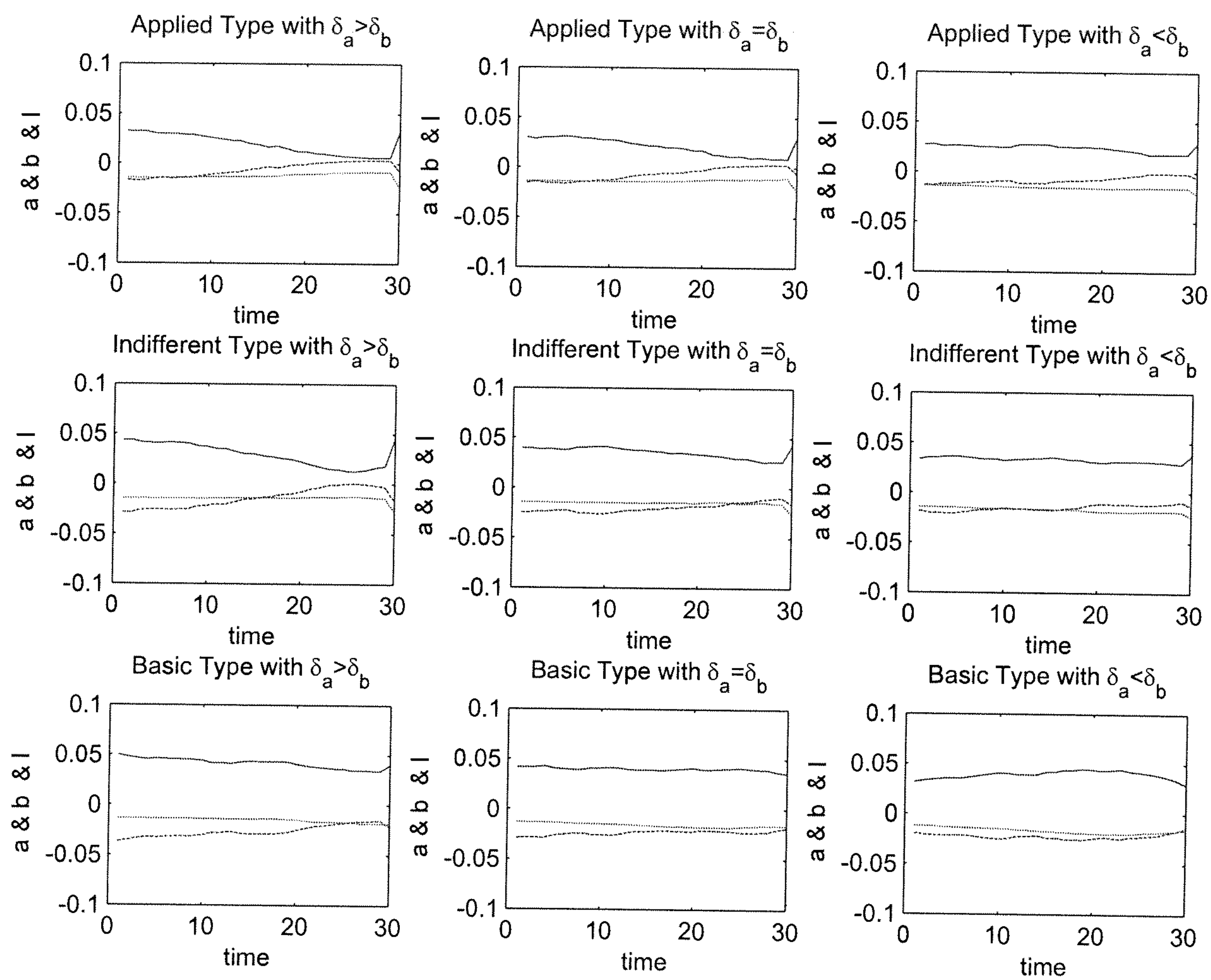

Figure 3a: Changes in Time Allocation due to Pasteur's Quadrant Effect

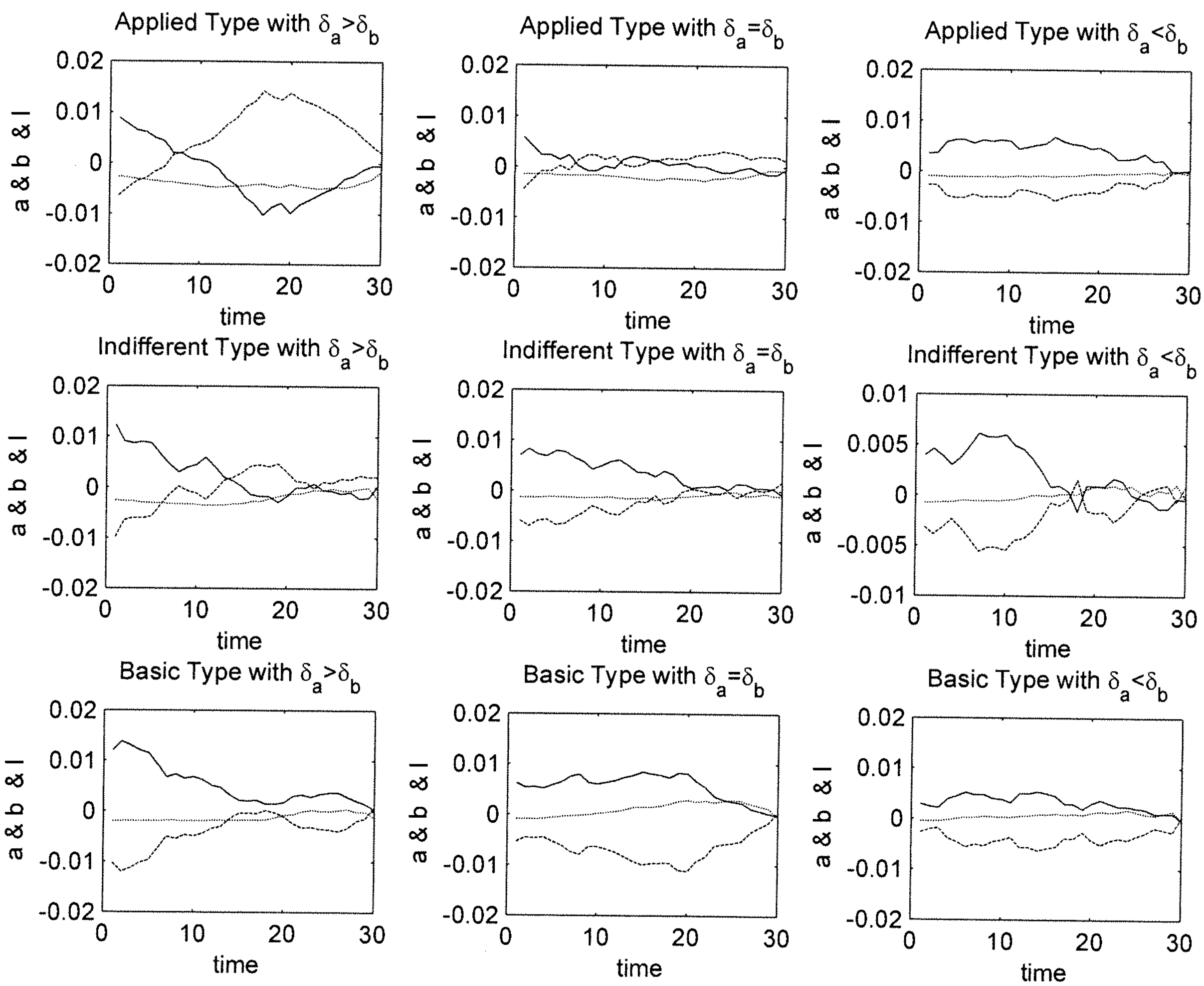

Figure 3b: Changes in Knowledge Stocks due to Pasteur's Quadrant Effect