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ACADEMIC OBSOLESCENCE AND INNOVATION

BE 750: Independent Study

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Submitted:

Introduction

A researcher's career is founded on their ability to contribute to their selected field of academia. The academic community including other scholars in the field, research institutes, and universities is the landscape where a researcher must build their career. Society, though not always conscious of the progress, seeks a more complete understanding of the universe. It is up to the academic community to provide this. When a scholar completes their academic training, they begin to work on advancing their own field by looking to answer novel questions. As they build a repertoire of skills and knowledge by conducting research, their academic reputation also grows. Scholars that are well-recognized are rewarded with larger incomes, notoriety, grants, and tenured positions at research institutions. The challenge is to quantify such a reputation into comparable metrics such that scholars may be compared.

For the purpose of this study, I present here the concept of academic capital: the total measure of a researcher's academic reputation and abilities. Research institutions, when trying to hire new faculty members, unknowingly consider the academic capital of a researcher. They consider their status and capabilities in terms of academic papers, citations, conference presentations and other contributions to the academic field. Typically, these measurements of contribution are an attempt to measure academic capital. Citation analysis and counting have risen from the need to effectively measure researchers' academic capital. The study of academic capital and the lifecycle of academic work also ties into understanding individual career choices and decision making.

Throughout their careers, researchers make a series of choices about where and how to invest their time. Each decision influences their academic capital either immediately or by altering the path they must follow to reach "success." As decisions are made and time passes, a researcher's once novel skills and techniques may become obsolete and inefficient. As a result, scholars interested in maximizing the return on their investments in knowledge and skills will be influenced by the rate at which that knowledge depreciates and the dependent variables.

The rate at which academic capital depreciates is not uniform or static. Among other factors specific to academic fields, innovations in tangential fields, information flow, and the onset of new technology could all alter the depreciation of a specific skillset and knowledge base. Some of these factors have recently developed in the academic landscape. Factors, such as new technology, will change certain fields of study much greater than others. The differences between field depreciation rates and the individual's focus on increased return on academic investment influences the direction of scientific progress. Natural incentives for academic investment, such as knowledge durability [McDowell 1982], are more apparent for certain fields of study. Researchers are rewarded for focusing academic efforts there.

This analysis seeks to understand the landscape of research that has been conducted on academic capital, depreciation, and productivity. First, I introduce a model which describes publication output and academic knowledge accumulation. I then describe two types of depreciation; publication depreciation and knowledge depreciation. Each depreciation type is characterized by specific variables. I review the concepts for these depreciation types and propose functions that describe their behavior. The models are used to further expand and differentiate research which has been conducted by other scientists.

Furthermore, I explore research which has been conducted on the onset of the technology age. Information accessibility and other types of technological innovation have altered the way which scientists work. These innovations are included in the two models for depreciation rates.

Finally, I present some recommendations on how to conduct an analysis of the innovation depreciation diversity across fields.

Model

Throughout the study, I will use the following terms frequently. Academic capital is defined as the stock of knowledge and skills used in the production of scholarship. Knowledge depreciation is the rate at which researchers' knowledge loses value once the knowledge has been accumulated. Publication depreciation is the rate at which researchers' publications lose value or relevance after publication has been accumulated.

For purposes of this analysis, publications will be treated as the principal academic output. In the following, publication output at time, t, is dependent on the time a scholar invests in research and their instantaneous academic knowledge. This can be represented by:

$$P_t = f(\, t_r, K_t)$$

where,

$$t_r = time\ spent\ on\ research\ activities$$

$$K_t = academic\ knowledge\ at\ time, t$$

Conceptually, publication output of a researcher increases as time and effort are invested in research activities: more academic knowledge and more effort spent on research activities yield a larger quantity of publications in the time period. Effort of the researcher is assumed to be optimized during each time period.[1]

[1] The effort that a researcher chooses to exert on research activities is both difficult to measure and endogenous. Although both effort and time spent on research activities are endogenous, research time is more easily quantifiable than effort. Accordingly, and consistent with prior research examining the incentives of academic researchers (see below), I will focus on time allocated to research.

Academic knowledge consists of the methods, skills, and facts needed to conduct research in a scholar's field of choice and itself requires effort to continue to create and maintain. As an example, an engineer must have a certain knowledge set containing math skills, application methods, and the ability to use current research technology to effectively study their field. An individual's current stock of knowledge consists of their prior accumulated knowledge, less any "depreciation," plus any newly acquired knowledge. This can be portrayed as

$$K_t = (1 - \delta_k)K_{t-1} + a_k$$

where,

$$K_t = academic\ knowledge\ at\ time\ t.$$

$$a_k = knowledge\ addition\ function, defined\ below.$$

$$\delta_k = knowlege\ depreciation\ , defined\ below.$$

From this model, there are two major observations to be made. The first is that the more effectively a researcher can acquire knowledge, the greater the total sum of academic knowledge. Similarly, the stock of academic knowledge will be greater the lower the rate of depreciation of academic knowledge. If a field of study has a greater depreciation rates, the resulting total stock of knowledge at time, t, will be diminished. Effective knowledge production counteracts or offsets the negative effect of depreciation.

The accumulation of knowledge is the intentional work done by a scholar to increase the breadth or depth of the knowledge set. An engineer who does not know how to run a simulation on a supercomputing system but learns to do so is accumulating knowledge. The individual ability of that engineer to acquire the necessary knowledge to run said simulation is a unique knowledge addition function, a_k.

The knowledge addition function is dependent on two major variables, namely, time spent on research activities (or knowledge accumulation), t_r, and the current knowledge, K_t.

$$a_k = g(t_r, K_t)$$

The accumulation of new knowledge increases with the amount of time a researcher chooses to invest in research activity. The greater the investment, the greater the contribution to the stock of knowledge. An engineer that elects to take an additional course invests the time in class, studying, and completing coursework and in return gains knowledge in the course topic. The ability to contribute to academia also depends on their current knowledge: the larger the current stock of knowledge a scholar has at their disposal, the greater quantity of academic contribution (or perhaps more efficient the contribution rate).

Continuing with our engineer example, when gaps are present in an engineer's knowledge, they will have to interrupt their academic work to fill these gaps before proceeding. An engineer who does not fully understand the fundamentals of fluid dynamics, while perhaps also not the best engineer, will be inefficient at contributing to academia due to continuous pauses. Meanwhile, an engineer with a robust understanding of fluid dynamic fundamentals and has invested time in expanding their knowledge base will more efficiently contribute.

Knowledge also depreciates over time. Depreciation of knowledge occurs due to factors like human nature, skill atrophy, new research, and method progress. As a researcher's career advances, previous knowledge may be forgotten from lack of application. An engineer focusing their time on fluid dynamics research may not be able to remember details about materials engineering. Similarly, application of skills will deteriorate. The ability to simulate a fluid dynamics problem, if left without practice, may be partially or completely forgotten. Other researchers will continue to conduct research to further their careers. This other novel research could make another scholar's previous work obsolete. Finally, research methods and theoretical methods progress as scholars work to innovate. These new methods can make older methods obsolete. Fortran 70, as an example, was once a reputable programming language that is now obsolete.

The rate of depreciation depends on two variables: time spent on research activities, t_r, and the rate of change of technology over the period, $\dot{T}$. $\dot{T}$ can be interpreted as the innovation over the time period. Research time investment negatively correlates with depreciation. Time invested in knowledge accumulation or by refreshing older material will reduce the depreciation rate. Another way to frame this concept is that time spent on activities that are not research (i.e. administrative duties) will increase depreciation rate of knowledge.

$$\delta_k = h(t_r, \dot{T})$$

Finally, the value of a researcher's past research output also declines over time. Research output, at time, t, is defined as the set of all contributions that a scholar makes to their chosen academic field. This includes, among other things, publications, conference presentations, and books. The production of publications is, as previously discussed, linked to a researcher's stock of knowledge. The value of these publications is frequently measured by how often a publication is cited (citation counting) or other forms of citation metrics. The value of past research output depreciates as well and at a different rate than academic knowledge. In isolation, a single publication has a lifecycle in which it increases in value, then decreases in value. The decrease can be caused by novel research, new methodologies, or new data. Novel research which results in publications will take the place of older and obsolete publications. Similarly, new information or new methods will also make older publications obsolete. We can represent this value of cumulative publications as

$$V_t = (1 - \delta_p)V_{t-1} + v(P_t)$$

where,

$$V_t = the\ value\ of\ a\ scholar's\ cummulative\ publications\ at\ time\ t.$$

$$v_t = the\ value\ of\ added\ publications\ in\ time, t.$$

$$\delta_p = the\ rate\ at\ which\ the\ value\ of\ prior\ research\ depreciates.$$

Similar to the knowledge expression above, the value of a researcher's current stock of publications increases when there is an increase in the production of new academic work and decreases the greater the rate of depreciation of previous work. This depreciation rate differs from than that the depreciation rate for knowledge: δ_p is the rate at which the value or relevance of research declines. An engineer that produces only publications which alter the fundamentals of fluid dynamics will have a low depreciation of the value of their publications as much future research will be founded off of these new fundamentals. However, an engineer that produces only research in a trendier topic, say drones, could have a higher depreciation of the value of the publications. The knowledge that both engineers have accumulated to produce these publications will depreciate at different rates than the academic publications.

This rate depends on developments in the academic field, e, and the rate of change of technology, $\dot{T}$, and is largely independent of an individual scholar's actions.

$$\delta_p = j(e, \dot{T})$$

The rate of publication depreciation will vary across fields, e, but will tend to be higher as the rate of change of technology increases.[2]

In sum, the model above identifies two types of depreciation. In the following discussion of the literature, I investigate and summarize studies that have uncovered information about each type of depreciation. A few studies have bridged the gap between these depreciation rates, and some have only sought to understand one or the other.

Literature Review

It is pertinent to understand the landscape of academic careers and publication behaviors. Above, I proposed a model that describes publication output and knowledge accumulation. Knowledge accumulation, while more difficult to quantify, has a longer research history. A majority of these studies seek to understand the reduction in potential during breaks in continuous research investment. It is thus natural to begin the literature review there.

[2] A positive technology effect could result in a decrease in the depreciation function depending on the nature of the innovation. We assume here that an increased change of technology will increase the depreciation of the value of current publications.

Research Lifecycle and Knowledge Depreciation

McDowell [1982] conducted a study analyzing the depreciation of knowledge and publication profiles over the course of an academic's career. In fact, McDowell's study touches both the academic depreciation and publication depreciation concepts discussed above. Much like the functions introduced in my model, McDowell's study introduces two similar equations.[3] He defines these two functions as:

$$L_t = \beta_0(s_t)^{\beta}$$

where,

$$L_t = gross\ addition\ to\ human\ capital\ stock$$

$$s_t = proportion\ of\ the\ existing\ stock\ of\ human\ capital$$

$$\beta_0 = the\ index\ of\ the\ individual's ability\ to\ produce\ human\ capital$$

$$0 < \beta < 1$$

and

$$\dot{K}_t = L_t - \delta K_t$$

where,

$$\dot{K}_t = change\ in\ accumulated\ stock\ of\ knowledge\ over\ time$$

$$K_t = human\ capital\ stock$$

$$\delta = rate\ at\ which\ knowledge\ depreciates$$

McDowell's δ is the same as my δ_k: the depreciation rate of knowledge. These definitions are very similar to those introduced in this study for total stock of knowledge and academic addition function.

[3] McDowell introduces a series of additional equations which characterize investment and production optimization during the research life of an academic. The details of these equations are outside of the scope of this study, but are tangentially reference in the summary of McDowell's work.

McDowell also introduces a concept called the durability of knowledge. McDowell defines this durability as the capacity for knowledge to continue to be relevant. The more durable knowledge is, the less quickly this knowledge will depreciate. The study connects the measure of knowledge a researcher has to their output (or, in this analysis' terminology, publications). After accumulating knowledge in an academic's early years, McDowell supposes, observed output will only continue to increase as accumulated knowledge is applied and used to produce academic pieces.

First, McDowell investigates the durability of knowledge. By referencing Solla Price [1965]'s work on citation decay and correlating these studies to literature decay rate, he reports an average annual decay rate of knowledge across several fields of study. This literature decay rate is a similar measure to the publication depreciation rate, δ_P, introduced in the model. He shows that physical and chemical sciences have the highest average annual decay rate. To combine these two depreciation rates, McDowell ties them to the discounted value of accumulated knowledge and subsequent cost of a year of interrupted service in an academic career. He concludes that researchers within fields with high literature decay rates (i.e. physical sciences) have larger reductions in returns by an interruption in career whereas those with low literature decay rates have a lower reduction in return. In the terminology of this study, fields with high levels of knowledge depreciation have the most to lose by a career interruption. Conceptually, the skillset of a researcher in a high depreciation rate field will have a faster lapse in relevance.

Secondly, McDowell studies the career publication profiles of these fields. His study of career publication profiles investigates the relative academic contribution over a researcher's lifetime. McDowell takes two samples of researchers and uses abstract publication to trace their careers between the ages of 20 and 60. His three-year moving average annualizes the output by age and depicts a frequency of these outputs. This effort shows that academic researchers who are in fields with less durable knowledge, such as physics, show a cyclical publication profile which indicates that they are constantly investing in knowledge that is pertinent to current topics of research. Meanwhile, humanities fields of research spend more time building durable knowledge bases, which leads to a larger and later peak later in their career. More generally, McDowell sees that fields that have a higher durability of knowledge delay output of academic contributions to later in life while those who have less durable knowledge focus more greatly on immediate output.

Finally, McDowell studies child-bearing and how it alters the academic careers of female scholars. Using the discounted value of knowledge and interruptions to academic careers, the study draws several conclusions regarding the ratio of women in academic pursuits and the opportunity costs of pursuing and developing a family. All of these conclusions tie to the depreciation of knowledge. McDowell was able to provide evidence that increased knowledge depreciation rates alter the career choices scientists make throughout their academic lifetime.

While McDowell sought to understand the opportunity cost of taking one year off from an academic career, there is also the question of academic motivation. McDowell's study quantified the cost of choosing activities that are not strictly related to one's career but did not seek to understand if all researchers are motivated strictly by income. Levin and Stephan[1991]'s study, discussed below, looks to test models of motivation for research career choices.

Levin and Stephan study the research productivity over the life cycle of a researcher across several disciplines. They review two frameworks for academic engagement decision making. One is investment-based and the other is "consumption-based." Investment-based theories suggest that scientists engage in activities based on future realized returns whereas the consumption-based theory suggests the motivation is seeking to solve the puzzle itself. Levin and Stephan continue on to show via analysis that only investment motivation drives research engagements.

As they explore the productivity of researchers as they age, Levin and Stephan note that a model of only investment-based motivation for research results in depreciating returns to investment as the time horizon decreases. Levin and Stephan use a regression model which accounts for several variables and corrects for a multitude of "individual fixed effects" such as the independent aptitude of a researcher.

After studying several fields of study in both Physics and Earth Science, Levin and Stephan conclude that productivity of researchers does display depreciation as the researcher ages. While this is not directly tied to knowledge depreciation, this phenomenon is reflected in the knowledge addition function discussed in this analysis. As researchers age, their willingness to invest in academic production decreases in 5 of the 6 fields that Levin and Stephan studied. This productivity decrease, Levin and Stephan elaborate, supports the investment-based theory of research motivation.

Their study also shows that education quality does not have a statistically significant reduction over time, that is, researchers that are educated more recently do not necessarily have an advantage over older researchers. Levin and Stephan elaborate on a few explanations of why this may be the case, including scientific revolution or an increase in total doctorate students. Additionally, the study hypothesizes that this productivity is decreased by the movement away from academic sectors seen in the 1980s. These factors relate to the model I presented above in that each factor that Levin and Stephan discuss could be altering the outcome of the depreciation rate.

Publication Production and Depreciation

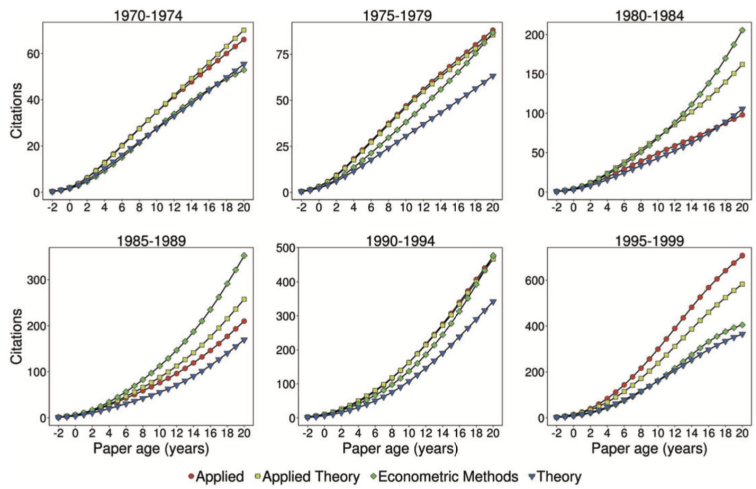
The secondary type of depreciation introduced in the model is publication depreciation. Research which has been done to understand academic production and publication depreciation is founded heavily on citation metrics and seeks to better understand how academic institutions assess the merit of scholars. Citation counting was first conceptualized in 1965 by De Solla Price in his study "Networks of Scientific Papers." In his study, he discusses the dynamic nature of citations and cited papers and the network that is built between all academic publications. Similarly, in 1965, Garfield et al. used citation index practices to study the publication output of Nobel Prize winners. The extensive early work done in the citation metrics field has allowed for more current studies to be conducted on the depreciation of citation rates and analyze the consistency of citation practices across academic disciplines.

Recent research analyzing the lifecycle of academic publication production acknowledges that understanding the differences in citation counting across disciplines is critical for successful evaluation of researchers. With the onset of technology and the increase of accessibility to understanding citation indices, several new patterns in citation practices have come to light. Much like Levin and Stephan's education quality phenomenon, citation practice changes will alter the results of a study in publication depreciation rate. Aside from the differences between fields, citations are occurring more frequently and the number of cited authors is increasing (Bastian [2015]). Just like in education, the number of citations is simply increasing due to the natural increase in the number of scholars. Additionally, modern citation practices in some disciplines include citing every contributor to an academic paper, regardless of their level of involvement. These differences in practices are pertinent for the present analysis. The ability to quantify publication depreciation is founded on homogeneous citation metrics if the intent is to make comparisons across sections of academic research. Several researchers have spent significant time seeking to understand publication depreciation and the differences between disciplines.

Anauati, Galiani, and Galvez [2016] completed a study which developed a method for quantifying the life cycle of scholarly articles specifically in economics. In their studies, Anauati et al. critiques the practices of using citation counts and analysis as a means of quantifying contribution of scholarly research as these practices have not been standardized across all fields of research, even within the economic field. The study argues that it may be that each field of study should have separate methods of quantifying performance and perhaps even separation within a field of study. Anauati et al. dives into the heterogeneity of the many facets of economic research publications.

By categorizing nearly 10,000 articles into one (and only one) of four fields, Anauati et al. applied natural language processing and web crawling to determine the citation distribution, on average, for each of the four fields of economic research. These are shown in Fig. 1.

Cumulative Citations Received per Year since Publication for the Average Paper across Fields of Research and Publication Dates Grouped into 5-Year Periods



Notes: Citations are smoothed using 5-year centered moving averages. Note that the *y*-axis scales vary across sub-figures.

Figure 1: Cumulative Citations for Average Article [Anauati 2016]

Figure 1 shows the cumulative citations for the average article by 5-year groupings (of publication date). According to Anauati et al., these figures reveal several phenomenona that alter our understanding of changing academic obsolescence. They note that, as time goes on, the volume of citations increases significantly. This is likely due to several factors: an increase of all peer-reviewed papers in the 20th century, an average increase of the number of citations in an academic piece, and the algorithms which power Google Scholar. Anauati et al. also notes that, as time has passed, differences in citation patterns have appeared across the various fields of economics.

Finally, Anauati et al. dives into the lifecycle question of academic work which is most relevant for the present analysis. There are two difficulties that affect this analysis that Anauati et al. introduces. These are the skewness of citations and citation inflation, as summarized above.

By using an ordinary least squares analysis, they were able to control for the effects of these challenges and plotted the effective lifecycle for each field of economics. This method shows that academic publications do indeed have a lifecycle. Figure 2 displays the results of this regression analysis.

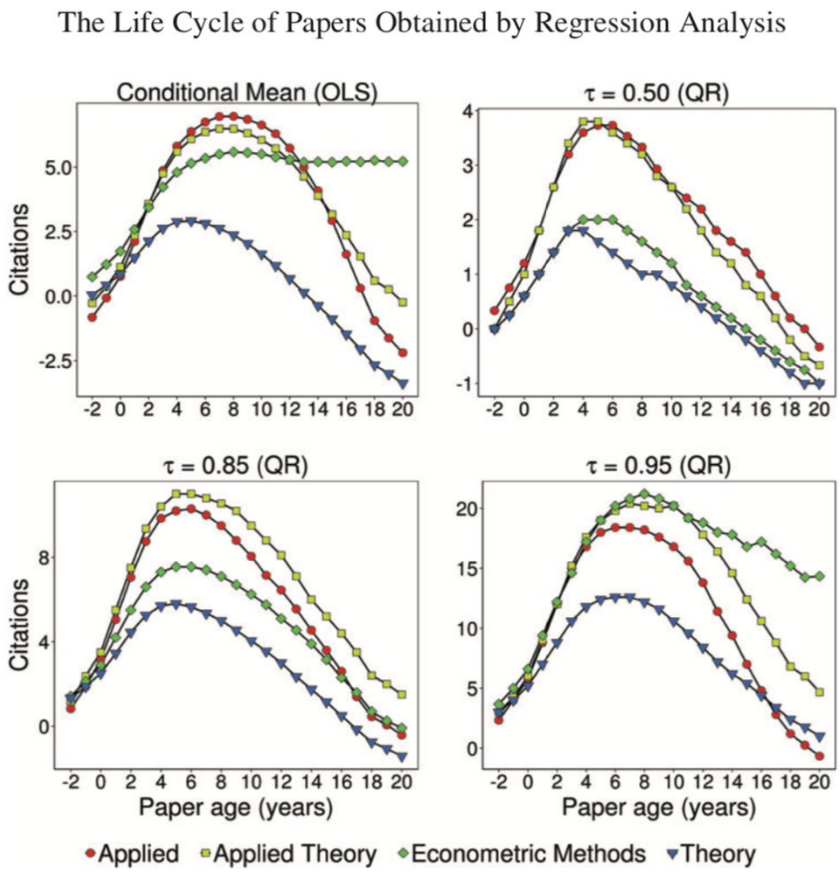


Figure 2: Regression Analysis Results [Anauati 2016]

Anauati et al.'s work shows that papers in economics typically reach their peak citations between 3 and 5 years after publication and after approximately 10 years receive negligible citations. These values can be used to approximate this analysis' publication depreciation rate for economic fields. Anauati et al. finish their study by concluding that it is apparent through their work that there is significant difference between sub-fields of topics of study. This indicates that citation counts, due to a lack of standardization, may not be the best metric to indicate research productivity. Overall, this study supports the idea that there are differences by field and within fields in research behaviors and citation practices. The study also gives an estimate for publication depreciation within economic fields of study. Finally, Anauati et al.'s work gives insight into how evidence can be collected to draw conclusions regarding how innovation and the information age alter publication depreciation across many academic disciplines. In fact, Galiani and Galvez [2017] does some of this analysis for us.

Galiani and Galvez[2017] use the same approach to analyze citation behavior across many fields of study. The study seeks to better understand how to effectively compare researchers across disciplines. Galiani and Galvez's study takes citations from 12 different fields and uses quantile regression to identify the lifecycle behavior. In their results, Galiani and Galveznote that citation inflation and skewness are present. This is shown by quantifying total number of citations by field, which vary widely, along with the percent share of total citations received at 2 and 5 years for each discipline. These two simple metrics begin to paint the picture for differences in citation behavior. This is especially relevant here as we dive into comparisons between industries over time.

Finally, Galiani and Galvez show the results of a quantile regression model on the data set. This is seen in Figure 3.

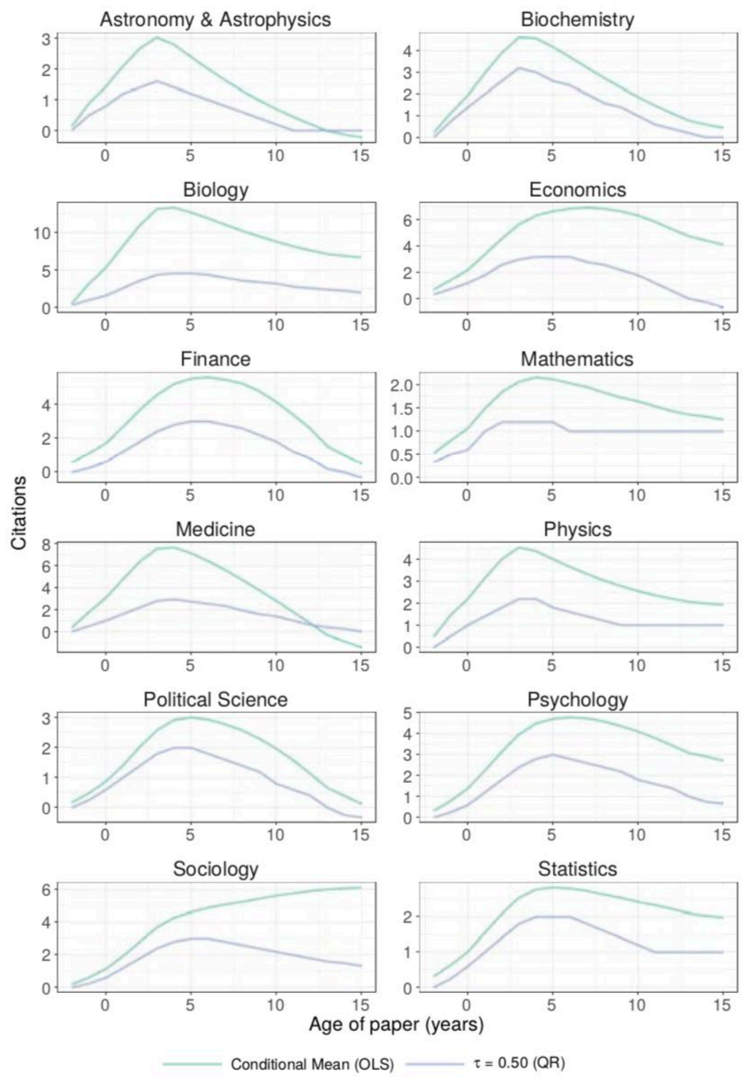


Figure 3: Estimated life cycles of citations of research articles [Galiani 2017]

Generally, they find evidence that all academic disciplines show evidence of a publication lifecycle. These lifecycles also vary by field, but generally display trends of increasing citations for a period after the publication is produced, a peak of citations, and then a diminishing citation count period. Social sciences exhibit longer cycle times while STEM subjects exhibit shorter cycle times.

The results of these two studies, which seek to quantify or model the production depreciation of specific academic pieces, inherently plays into the decision-making of academic researchers as they choose whether or not to enter certain fields of research. An academic discipline which has a greater depreciation rate will deter scholars because this increases total investment required to achieve the same level of "success.". Thus, the citation patterns and publication depreciation of each field are key criterion for the choices researchers make in academic investment and how they output academic work.

The Information Age

As the information age has progressed, it is natural to question whether the flow of data or other innovations has altered academic capital, research productivity, or the lifecycle of an academic publications. There are several different ways in which technological advances can alter academic contribution. Technology can progress by improving accessibility, increasing communication methods, development of new methods or tools, and the creation of new physical technology.

Improved accessibility could increase publication depreciation rate. As data becomes more accessible, novel research will be easier to perform, thereby making previous research quickly obsolete. An engineer who can Google scholarly articles about fluid dynamics will be faster to produce novel research than the engineer who must manually scrub through the journals at the library.

Easing the flow of communication will alter depreciation rate, but it's unclear if this is negatively or positively correlated. Some studies have already sought to understand this. It could be that an increase in communication decreases the depreciation rate because scholars will hear about novel research sooner and be able to begin conducting even more novel research faster. However, communication increases may also make researchers less efficient, thereby increasing the depreciation rate, due to an increase in distractions. Our hypothetical engineer who spends their entire day chatting friends or scholars on Facebook will likely not produce novel research anytime soon. They may, however, find out more quickly about novel research and come up with interesting proposals more quickly.

New methods and tools are the most straightforward innovation that changes depreciation rates. As methodologies are improved and augment scholarly research, scholars become more efficient at making old research obsolete. These new methods and techniques allow researchers to accomplish tasks such as process large quantities of data and use natural language processing to count through thousands of publications. The fluid dynamics engineer who learns to use large data processing to handle his experimental values will produce research more efficiently than the engineer who must hand calculate each equation.

Finally, physical innovation has enabled significant advances in research. The invention of the GPU, as an example, as allowed for geophysicists to better understand weather patterns and movements. Large-scale dynamic modeling and processing is finally available where this may not have been the case before. The advent of a large physical innovation, such as a computer, will increase depreciation rate as the research cycle will correspondingly increase. Our final engineering example: the engineer with the ability to accelerate their fluid dynamics simulation onto the GPU will be much faster at running simulations than the engineer who is still struggling through Fortran punch cards.

The following studies have all sought to better understand some aspect of these technological advances, but little has yet been done to correlate publication or academic depreciation rate with innovation.

Kaminer and Braunstein [1998] used bibliometric analysis to understand how the usage of various network applications have altered productivity of researchers. By evaluating process logs and conducting surveys, Kaminer and Braunstein were able to use principal component analysis and regression to estimate models for how much internet usage had altered productivity. Kaminer and Braunstein found that internet use, in general, positively correlates to productivity of a researcher, thereby increasing the rate at which a researcher can accumulate knowledge. The study notes that internet use can improve productivity by one half the amount of productivity gained by an increase in age from the time since PHD granting. Programs that are analyzed in the study are relatively limited and certainly the variety of innovations available has increased significantly since 1998. Additionally, Kaminer and Braunstein's main focus is on increased communication where other factors may be greater drivers for present research productivity.

Heimrik and Vasileiadou [2008]'s study begins to differentiate between communication improvements and information accessibility in productivity. The study argues that there is much work to be done in understanding the internet as a research object and studying whether its use has altered career decisions or shifted research behavior. Heimeriks and Vasileiadou's study is continued in a later study conducted by Vasileiadou and Vliegenthart[2009]. Vasileiadou and Vliegenthart's work explores the actual productivity of researchers in the era of the Internet. Building on the work in Heimerik and Vasileiadou's study and several others (Walsh et al. [2000] and David and Steinmueller [2003]), Vasileiadou and Vliegenthart use two case studies to investigate the link between internet usage, communication, and research productivity. Using multi-variate analysis on the two case studies, the research was able to conclude which pieces of the information age more drastically changed productivity. Face-to-face communication showed an improvement in research productivity while online communication, such as emails, had an insignificant effect on productivity. While this topic is not directly relevant to the present discussion, it is important to note that improved online communication may not have significant effects on productivity thus our analysis can be limited in scope to information accessibility and the rate of innovations.

Waverly et al[2010] investigated how DNS (domain name system) and BitNet have changed research productivity. Using a Poisson quasi-maximum likelihood estimator, the study was able to conclude that, generally, internet usage increases both research productivity and communications. However, the most notable finding is that the data suggest that lower-tier research institutions realize a larger benefit from internet usage then higher-tier institutions. On average, research productivity improves ~8% across all tiers, but the lowest-tier universities see an improvement of 18%. Additionally, this phenomenon also holds true for female scientists. Women researchers realize a larger benefit from internet usage than their male counterparts. The corollary is that elite-institutions see minimal (possibly negligible) benefits from information accessibility.

While these studies begin to address how internet usage alters research productivity, they typically focus on either a broad approach which could have difficulties due to the differences across fields for citation counting practices or they focus on a singular cross-section of industry to study. The question at hand is whether the information age has specifically altered the decision-making of academic researchers due to change in either the publication or the academic depreciation rates of different disciplines. It is a necessary next step to study changes in publication depreciation rates and the academic addition function for different fields and determine which, if any, have been significantly altered by technological innovation.

Conclusions

From experimental research and the hypothesized model, we can draw three major conclusions. (1) Knowledge depreciation and research productivity are inherently difficult to quantify. The research which has been conducted focuses on the positive correlation between time investment in other activities and decreased productivity rates. Individual researcher effects are decision variables which are difficult to quantify. The absence of academic production can be calculated; however, the actual academic production function is hard to characterize empirically.

(2) Publication depreciation has been quantified by several researchers already. These decay rates are dependent on field-specific citation practices. Despite this, the methods by which Galiani and Galvez [2017] and Anauati et al. [2016] are able to calculate decay rates across several research fields would allow us to calculate a δ_p across diverse research fields. Comparable publication depreciation metrics would then be used to further explore how these rates have changed in time. The hypothesis is that some fields which have high rate of innovation would also have higher or increasing depreciation rates.

(3) Technology effects (information access, innovations, and communication flow) have been shown to be positively correlated with research productivity. These studies are limited to understanding how technology makes researchers more able to produce academic research or increase stock of knowledge (i.e., how technology has changed the academic production

function). There are currently no studies which investigate the correlation between technology and depreciation of either publications or knowledge.

The combination of understanding the rate of innovation within a field of study and its publication depreciation rate would refine our current understanding of individual decision making and career choices. Conceptually, if technology significantly increases the depreciation rate for a specific field, then researchers may choose not to enter that field. The academic investment required to maintain a competitive skillset may become so great that scientific progress is directed towards research which has a less significant depreciation. As we seek to understand individual career choices — the further the foray into the technological age — the more important it will be to understand how technology changes academic capital.

Proposal

Throughout this analysis, I have presented the separation between knowledge depreciation and publication depreciation. These rates have been studied by several scholars previously, but the intersection of these rates and their dependency on innovation has yet to be fully understood. I propose a future study which investigates publication depreciation rates, in a similar method to Anauati et al's study, across several academic disciplines in time periods of increased innovation. I would seek to understand how these innovations correlate with publication depreciation and which types of innovation more heavily alter the rate. The way in which technology changes depreciation rates will alter academic career choices and decision making. Understanding these changes will lead to a greater understanding of the future of scientific progress.

References

Anauati, V., Galiani, S., & Gálvez, R. H. (2016). Quantifying the life cycle of scholarly articles across fields of economic research. *Economic Inquiry*, *54*(2), 1339–1355. https://doi.org/10.1111/ecin.12292

Bastian, Hilda. (2015.) “Science and the Rise of the Co-Authors.” Blogs.Plos.Org.

David, P. A., & Steinmueller, W. E. (2003). Introduction. *Economics of Innovation and New Technology*, *12*(1), 1–3. https://doi.org/10.1080/10438590303122

De Solla Price, Derek J. (1965). "Networks of Scientific Papers." *Science*149, no. 3683 : 510-15. www.jstor.org/stable/1716232.

Galiani, Sebastian, and Galvez, Ramiro H. (2017). “The Life Cycle of Scholarly Articles Across Fields of Research.” *SSRN Electronic Journal*, May. https://doi.org/10.2139/ssrn.2964565.

Garfield, Eugene. (1979). “Citation indexing - its theory and application in science, technology, and humanities.” New York: Wiley.

Greene, Mott. (2007). “The Demise of the Lone Author.” *Nature* 450 (20): 1165. https://www.nature.com/articles/4501165a.pdf.

Hamermesh, Daniel S. (2018). “Citations in Economics.” *Journal of Economic Literature* 56 (1): 115–56. https://doi.org/10.1257/jel.20161326.

Hamilton, D. (1991). “Research Papers: Who's Uncited Now?” *Science, 251*(4989), 25-25. Retrieved January 15, 2020, from www.jstor.org/stable/2875025.

Heimeriks, G., & Vasileiadou, E. (2008). “Changes or transition? Analysing the use of ICTs in the sciences.” *Social Science Information*, *47*(1), 5–29. https://doi.org/10.1177/0539018407085747

June, Audrey Williams. (2018). “Ex-Administrators Reveal the Secret That Eased Their Return to the Faculty.” *The Chronicle of Higher Education*.

Kaminer, N., & Braunstein, Y. M. (1998). Bibliometric analysis of the impact of internet use on scholarly productivity. *Journal of the American Society for Information Science*, *49*(8), 720–730. https://doi.org/10.1002/(SICI)1097-4571(199806)49:8<720::AID-ASI6>3.0.CO;2-V

Lazear, Edward P. and Katherine L. Shaw (2007), “Personnel Economics: The Economist’s View of Human Resources,” *Journal of Economic Perspectives*, 21 (4): 91-114.

Levin, Sharon G, and Paula E Stephan. (1991). “Research Productivity Over the Life Cycle: Evidence for Academic Scientists.” *American Economic Review* 81 (1): 114–32.

McDowell, John M. (1982). “Obsolescence of Knowledge and Career Publication Profiles : Some Evidence of Differences among Fields in Costs of Interrupted Careers.” *American Economic Review* 72 (4): 752–68.

McDowell, John M., Larry D. Singell, and Mark Stater. (2011). “On (and off) the Hot Seat: An Analysis of Entry into and out of University Administration.” *Industrial and Labor Relations Review* 64 (5): 889–909. https://doi.org/10.1177/001979391106400503.

Siow, Aloysius. (1998). “Tenure and Other Unusual Personnel Practices in Academia,” *Journal of Law, Economics, and Organization* 14 (1): 152–73. https://doi.org/10.1093/oxfordjournals.jleo.a023395

Taylor, Susan Washburn, Blakely Fox Fender, and Kimberly Gladden Burke. (2006). “Unraveling the Academic Productivity of Economists: The Opportunity Costs of Teaching and Service.” *Southern Economic Journal* 72 (4): 846–59. https://doi.org/10.2307/20111856.

Tuckman, Howard P., and Robert P. Hagemann. (1976). “An Analysis of the Reward Structure in Two Disciplines An Analysis of the Reward Structure in Two Disciplines.” *Journal of Higher Education* 47 (4): 447–64. http://www.jstor.org/stable/1978729.

Vasileiadou, E., & Vliegenthart, R. (2009). “Research productivity in the era of the internet revisited.” *Research Policy*, *38*(8), 1260–1268. https://doi.org/10.1016/j.respol.2009.06.005

Walsh, J. P., Kucker, S., Maloney, N. G., & Gabbay, S. (2000). “Connecting minds: computer-mediated communication and scientific work.” *Journal of the American Society for Information Science and Technology*, *51*(14), 1295–1305. https://doi.org/10.1002/1097-4571(2000)9999:9999<::AID-ASI1046>3.0.CO;2-W

Waverly W, D., Sharon G, L., Paula E, S., & Anne E, W. (2010). “The impact of information technology on academic scientists’ productivity and collaboration patterns. “*Management Science*, *56*(9), 1439–1461.