An Inquiry Into The Determinants of Research Sector Productivity

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This paper constitutes an inquiry into the determinants of research sector productivity. Three variables thought to be relevant in determining the productivity of the research sector of an economy are proposed and examined on the basis of Paul Romer's (1990) model of endogenous economic growth. The productivity of the research sector in the aforementioned model of economic growth is conceived to be a function of the three variables proposed in this paper. These three are *openness in the research sector*, *market conditions* for research, and *access to the stock of knowledge*. The aim of the paper is to inquire into the character of these variables and their influence on the productivity of the research sector.

Keywords: Innovation, Endogenous Growth, R&D, Romer model

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1. Introduction

Economic growth is undoubtedly a central feature of modern life. It is the core of what most people broadly call “progress”. It is the slow, uneven and yet persistent emancipation from want, underpinned by our increasing understanding of the world around us. From longer, healthier lives, increasing prosperity, and a steady stream of novel innovation, economic growth incessantly broadens our conception of what is possible. It is this phenomenon, constituting the unmatched increase in human welfare over the last few centuries which is the subject of this thesis.

This paper proposes a few factors which may be at play in determining the ability of society to produce new knowledge. The three proposed variables are *openness in the research sector, market conditions for innovation,* and *access to existing knowledge.* The aim is not to provide a full picture of the productivity of the research sector, but rather to openly inquire into the causes of higher or lower productivity in research.

The chosen variables are not the result of empirical research, but rather aim to propose a development of an existing theory. The variables proposed have been brought about through an overview of literature pertaining to the productivity of the research sector, and from the premises and assumptions made in Romer’s (1990) model of endogenous technological change and economic growth

The classic model of economic growth is the one devised by Robert Solow in 1956. Its theorization of the interplay of factors determining an economy’s long run growth trajectory laid the foundations for subsequent theoretical developments. His central insight was that when an economy is in its so-called “steady state”, defined as all variables growing at a constant rate, the pace of growth is equal to the pace of technological development (Jones & Vollrath, 2013). The conclusion however, does not fully explain growth as technology is exogenous to the model.

That technological innovation and development is of central importance to growth can seem intuitive. Improvements in technology increases the productivity of laborers, enabling an economy to generate more or better outputs from the same inputs (Jones & Vollrath, 2013). Letting technology be exogenous to a growth model thus greatly limits its explanatory power. While the Solow model theorizes the role of capital and the size of the labor force, the exogeneity of technology in the model left an opening for future theories.

This brings us to the endogenous growth models that have since come to the fore, specifically Paul Romer's (1990) model of endogenous growth. Romer's conclusions have many similarities with Solow's, the difference lying in the fact that the conclusion that steady state growth is equal to growth rate of technology is not the end of the analysis.

The point of departure for this paper is the equation illustrating the rate of change in the level of technology in Romer's (1990) model of endogenous growth. Specifically the variable accounting for productivity in the research sector. In the original version of the model, the change in technology was proposed to be a function of the productivity of the research sector, human capital employed in research, as well as the prevailing level of technology. This function is expressed mathematically by Romer (1990) as follows:

$$\dot{A} = \delta H_A A. \tag{1}$$

The change in the level of technology is a function of the human capital employed (H_A), an index of the existing amount of knowledge (A), as well as a productivity measure (δ). The rate of change in the level of technology ($\dot{A}$) is analogous to the production of the research sector, as the innovations produced by the research sector in turn constitute the level of technology (A). Thus, the production of the research sector conveys the rate of change in the level of technology. It is the productivity measure δ which the proposed variables are thought to determine.

The variable accounting for productivity in the research sector is a function of factors not easily studied through econometric methods. At its core, the business of research is a creative industry, and is therefore somewhat different from other sectors of the economy. The basis for this is the simultaneous non-rivalry and excludability of ideas, which in Romer's model are designated "designs".

Throughout this text, in place of the terms “ideas” and “innovations”, the term “designs” will be applied. Designs are defined as instructions for working with raw materials, and are produced by the research sector. This terminology and characteristics of designs are discussed further in section 3.3 and 3.4.

This text aims to propose that the productivity of the research sector is a function of several identifiable variables. While these do not constitute an exhaustive list, they may serve as potential points of departure for future research into this question. In this paper I propose that the productivity of the research sector is a function of variables including the following three. As stated in the introduction, these are *openness in scientific practices*, an economic framework incentivizing innovation, meaning *market conditions*, and the *general accessibility of the knowledge* required to innovate. The reasons for these factors being important to the research sector are outlined in the beginning of each of the variables' individual sections.

There are potentially innumerable factors which play a part in determining the productivity of research, some of which may be nigh on impossible to quantify or study systematically. In conceptualizing a function explaining the productivity of the research sector and specifically the productivity parameter in Romer’s model, the inclusion of a term representing those factors not included could usefully account for the complexity of the variable. For reasons of simplicity however, this “other” term is not discussed in this paper. However the above three have been included because they in some sense are related to some of the basic features of a productive research sector, as well as to important aspects of Romer’s (1990) model.

The first proposed variable is the *openness* of research institutions. The degree to which researchers are able to collaborate and compete with others, as well as the tendency to resist stagnation of working practices and modes of thinking likely impact the ability of an institution or network of institutions to produce new insights. The second variable is the *market conditions* in which research takes place. As in much of economics, this variable weighs between the dynamic benefits of vigorous competition and the economies of scale provided by large firms. The final variable is practical *access to existing technology*. An assumption made by Romer in determining his equation for the development of technology is that the research sector in aggregate has access to the total stock of knowledge. However it seems likely that there may be many ways in which a researcher or institution may not have access to certain knowledge and designs. The degree to which a society is able to convey new insights to those who can use them in the production of new designs thus seems likely to have a large impact on the productivity of research.

The contents of this paper are structured as follows. Overall, the text can be divided into three parts. The first part, sections 1-3, contains the introduction, an overview of the literature, and an exposition of the most relevant aspects of Romer's (1990) model of endogenous growth. Taken together, these constitute the backdrop for the main arguments of the text. The second part is made up of sections 4 and 5. In section 4, each of the three variables is proposed and discussed on the basis of relevant literature. Section 5 outlines the potential mathematical characteristics of each variable. Finally, section 6 contains the conclusion and reiterates the main arguments of the text.

2. Overview of the Literature

This section contains an overview of the literature on economic growth most closely related to the questions raised in this paper. Specifically, endogenous growth theory and the production of new technology. Thereafter the main sources used in the paper will be outlined.

The theory of economic growth is structured largely on the interplay between three main variables. These are capital (*K*), labor (*L*), human capital (H) and technology (*A*). The variable labor in some cases represents the labor force, and in some cases the population of the economy. *L* grows at the rate of population growth, *n*. Labor is at times exchanged for the variable human capital (*H*), which can be used to represent the varying levels of education required to work in different areas of the economy.

These four very broadly outlined variables interact in growth theories to model the growth of an economy. For the purpose of this paper, the focus will be on the growth rate of the variable technology, commonly denoted as *A*.

2.1 Exogenous and Endogenous Growth theory

As stated in the introduction, Solow's article, "A Contribution to the Theory of Economic Growth" laid the groundwork for modern research into the nature and causes of economic growth. His conclusions regarding the centrality of technological development have proven to be durable (Prescott, 1988) The central insight presented by Solow is that the rate of growth when all variables are held constant is equal to the growth rate of technology. However, the variable *A* is exogenous to the Solow model, whereby the causes of change in the growth rate of *A* are not explained, but rather taken as given (Jones & Vollrath, 2013).

Following Solow's theory are so-called endogenous growth theories. These theories account for the growth in the level of technology available to the economy. The basis of this paper is Paul Romer's (1990) theory of endogenous growth. The dynamics of the model are similar to the Solow-model, with a central development being the addition of an equation accounting for the rate of growth in the level of technology. Here, the growth in technology is a function of the current level of technology, the human capital devoted to its production, and the productivity parameter which is the subject of this paper (Romer, 1990).

The Romer's model has since been augmented by Jones (1995) through the addition of the exponent ϕ to the parameter A as well as the exponent $\boldsymbol{\lambda}$ to the parameter H_A in equation (1). Adding ϕ as an exponent to A, enables the influence of greater technology to be either positive or negative, depending on the sign of ϕ. Adding the exponent $\boldsymbol{\lambda}$ to H_A allows for diminishing returns to increasing the amount of human capital deployed in the research sector. These changes are discussed further in section 3.4 and 4.3.

Another influential endogenous growth model is the one proposed by Aghion and Howitt (1992). The production of new technology in the Aghion-Howitt model is structured around the concept of creative destruction as first described by Joseph Schumpeter. Creative destruction, Schumpeter contends, is the basis for the incessant change and disruption which characterizes a market economy. It is the process by which older products and services are outcompeted by improved iterations of themselves, or by entirely new innovations opening up new markets and changing conditions of consumption (Schumpeter, 1942). The Aghion-Howitt model therefore relies on a stochastic process for the development of new designs, meaning that technology in the model grows at a rate determined by random increments between levels of technology (Aghion and Howitt, 1992).

Another important difference between the two, is the Aghion and Howitt model's differentiation between "vertical" and "horizontal" innovation. Vertical innovation means an improvement in the quality of an extant good or service. Vertical innovation thus serves to supplant the versions of goods and services available at any given time, with newer, improved iterations of the same. It can be thought of as building on current technology to improve offerings on the market. Horizontal innovation on the other hand means the introduction of entirely new products and services to the economy. Instead of building on what is currently on offer, horizontal innovation expands markets through the introduction of new products (Aghion and Howitt, 1992). An example of the difference between the two would be the difference between innovation consisting of a new and improved version of a car, with better mileage and comfort and innovation consisting of the invention of the automobile .

2.2 Endogenous growth theory, Stochastic or Deterministic Technological Change

In terms of the production of new research, the two models differ mainly in how the growth rate of technology is determined. In Romer's model, the growth rate of technology is deterministic and constant, while in Aghion and Howitt's model it is determined by a stochastic process, wherein new designs arrive at random intervals. In this section, the suitability of a deterministic process for the purpose of this paper is determined.

From the perspective of this paper, concerned with the variables underpinning the productivity of the research sector, the most important difference between the two theories is that between a stochastic and deterministic innovation process. The equation illustrating the arrival rate of new designs in the Aghion and Howitt model doesn't contain a productivity parameter for the research sector. Instead, it contains a random variable indicating the interval between each design. The size of this variable is random, and innovation is dependent on variables impacting the probability of a new design occurring. While the model allows for changes in policy impacting the probability of innovation, this element of chance makes it more difficult to attempt to determine the variables of which research productivity is a function.

Therefore, Romer's deterministic model of innovation is more appropriate for the purposes of this inquiry into the productivity of the research sector. The productivity parameter in his equation illustrating the rate of innovation can more easily be described through a function containing the variables which are the subject of this paper.

2.3 Overview of the Main Sources

As outlined in section 2.2, the point of departure for this paper is Romer's (1990) model of economic growth. His theorization of the economy into the research, intermediate, and final-goods sectors places the research sector as the engine of the remaining two sectors. The equation governing the production of the research sector, that is, the rate of change in the level of technology, contains a parameter for productivity within that sector (δ). This thesis proposes three variables of which δ may be a function, *openness*, *market conditions* and the *accessibility of knowledge*. In this section the main sources used for the analysis and discussion of these variables are outlined.

The basis for *openness* as one of the variables is Joel Mokyr's (2005) research on the development of European intellectual life which formed the conditions for modern economic growth. He argues that the emergence of positivist philosophy encouraged the accumulation of "useful knowledge". That is, knowledge with practical applications for economic life. Together with these developments, Mokyr accounts for the adoption of practices categorized as "open science". These include new means of categorizing and communicating knowledge for the benefit of a growing community of researchers, as well as a culture of skepticism and transparency (Mokyr, 2005). These improvements in the accumulation of knowledge and lowering of barriers to engage in research and innovation preluded the development of the research sector as conceived of in Romer's model.

The influence of *market conditions* on research productivity has been studied by Arora, Belenzon, Patacconi and Suh (2019) in research on the declining prevalence of corporate research in the United States. They argue that a shift from research conducted in-house by corporations to more research being conducted in universities and commercialized through start-ups based on a specialized technology has had adverse effects on the productivity of the research sector.

Another perspective on the influence of *market conditions* on research productivity comes from studies done on the use of patenting. Findings by Webb, Short, Bloom, and Lerner (2018) indicate an increase in the use of patents as a tool for asserting market power rather than the protection of new designs. A study by Lerner (1995) on new biotechnology firms indicates that high litigation costs relating to patenting increases barriers to innovation within the sector, as firms seek to avoid patent-litigation. Specific practices used by incumbent firms to deter or co-opt competition from improved or alternative designs are described by Cohen, Nelson and Walsh (2000) as well as Cohen, Goto, Nagata, Nelson, and Walsh (2002).

The third variable, *access to knowledge* is closely related to the parameter A in equation (1), representing the stock of knowledge. The changes to equation (1) proposed by Jones (1995) are discussed in further detail in section 3.4 and 4.3. Mokyr (2005) is also an important source for the discussion of this variable, together with the sources named below.

Research by Bloom, Jones, Van Reenen, and Webb (2020) finds a general decline in the productivity of the research sector in the United States measured by a variety of metrics. Potential explanations for this apparently increased difficulty of finding new ideas for designs have been proposed by Jones (2009) in his account of the effect of the increasing size of the total stock of knowledge. Specifically, the increasing amount of education required for an individual to reach the proverbial “frontline” of knowledge in a given field. Jones argues that the consequence of this is an increase in the degree of specialization and in collaborative research. Findings by Wuchty, Jones & Uzzi (2007) indicate that collaborative, team-based research has been steadily growing in proportion to research conducted by individuals for several decades.

3. The Romer model and The Specialness of Designs

This section outlines the most relevant aspects of Paul Romer's (1990) model of endogenous growth. The Romer model upon which this paper is based, is itself predicated on the centrality of designs to growth. The mechanics of the Romer model are structured upon certain economic characteristics exhibited by designs, creating the market conditions which are then analyzed.

First, the three premises on which his argument is based are accounted for, followed by the three sectors which make up Romer's model of the economy. Finally, the equation describing the production of the research sector is discussed in more detail, focusing on the parameter accounting for the rate of change in the level of technology (δ).

3.1 Romer's Three Premises

Romers proposed model of growth is based on three premises. The first is that technological development and innovation is of central importance to economic growth. This notion follows from the work of Solow and his conclusion that the steady state rate of growth is equal to the rate of growth for technology (Jones & Vollrath, 2013). The second premise is that technological innovation takes place in a market, with actors responding to economic incentives.

The third, most important premise regards the nature of technological designs as products on a market. Romer makes the distinction that inventing a method with which to work with raw materials is fundamentally different from other economic goods. Once a design for converting raw materials into a producer good which can then be used to produce further goods for consumption, the cost of using said design again is zero. In this sense, an investment in technology is equivalent to incurring a fixed cost (Romer, 1990).

This constitutes designs having the characteristic of being nonrivalrous, yet simultaneously being partially excludable. That designs are nonrivalrous follows from their very nature. Since they can be conveyed from one person or institution to another at virtually no cost, as well as being able to be used an infinite number of times in a potentially equal number of ways, the use of a design by one firm does not in any way hinder its use by another. Therefore designs are nonrivalrous.

However at the same time, it follows from Romers second premise, as well as empirical observation that they must be at least partly excludable. The second premise on which Romer's model is built is that the individuals and institutions which produce designs are acting in response to market incentives. This premise is supported by the fact that a significant percentage of research and development in advanced economies is conducted by the private sector. Since 2005, business enterprise research and development (BERD) spending has increased from an average of 1,02% to 1,4% of GDP in OECD countries (author's own calculations based on OECD (2022)). As the total amount of resources expended on research by advanced economies is significant, it stands to reason that there is an expectation of future profit from the investment. This implies that the results of this research, the designs produced, are in some sense exclusive, as firms expect to be able to prevent others from immediately profiting off of their research.

The exclusivity of designs is largely a function of the legal system. The aim of laws protecting intellectual property rights, such as a patent system, is to provide the necessary incentives for research and development to take place in the market. At the same time, patents do not convey an indefinite monopoly on their holder, but rather expire after a period (Griliches, 1990). This is to enable the economy to take advantage of the nonrivalrous characteristic of designs. In this sense technological development itemized as designs are both nonrivalrous and partially exclusive.

Here, Romer makes a distinction between when a design is nonrivalrous and when it is excludable. The patent system enables the originator of a design to prevent others from using it in the same way as the inventor. A particular design for a process or product cannot be copied if it has been patented. At the same time, there is nothing hindering other actors from using the first patent to produce derivative designs, provided they are sufficiently different. Thus, from the perspective of the intermediate goods sector using designs to make producer durables, a design is excludable. At the same time the design is available to all from the perspective of the research sector. The characteristics and workings of the patent system have an important effect on the *market conditions* for innovation, something which will be discussed in more detail in section 4.2

3.2 Romer's Model of the Economy

Romer's model is based on four inputs and three sectors. The four inputs are capital, labor, human capital, and the stock of knowledge. Capital is defined in terms of foregone consumption, or savings, and is measured in units of consumer goods. Labor is measured in an amount of people, and is defined as the skills emanating from a healthy person. Human capital is separate from labor, and is defined in terms of years in education and training in the workplace. These four inputs are then used for production in three formal sectors structured as a kind of supply chain. The final products of this supply chain are consumer goods which can be either consumed or converted into capital (Romer, 1990).

The first sector is the research sector. It makes use of human capital and the existing level of technology to produce new ideas and innovations, henceforth termed "designs". These new designs are defined as instructions for working with raw materials. The designs are then used by the intermediate-goods sector together with capital to make producer durables, such as industrial machinery or processes. These producer durables are subsequently used in the final-goods sector in the production of consumer goods. The final-goods sector uses the producer durables together with labor and human capital to produce consumer goods which are then either consumed or saved and converted into capital.

3.3 Definition of "Designs"

The definition of designs is the one put forth by Romer, wherein designs correspond to the products of the research sector. Here, designs are conceived of as instructions for combining raw materials in order to produce goods. The research sector uses as an input the total stock of knowledge, however when this is transferred to the intermediate goods sector, it is as itemized designs, or sets of instructions which are then used in the manufacturing of produced durables (Romer, 1990). Therefore new insights and knowledge produced by the research sector can be thought of as individual items which together make up the total stock of knowledge.

Although terms such as "ideas" and "innovations" may at times seem more natural, the use of the term design aims to maintain the theoretical framework of Romer's model. This framework naturally applies to the productivity parameter in the equation describing the research sector, thereby also constituting the framework for the proposed variables.

3.4 Discussion of the Research Sector

For the reasons stated in section 1.1, the main focus of this paper is the research sector and its productivity. Building on Solow's conclusion that technological growth is the driver of economic growth, Romer's model has many similarities to the Solow model, with the addition of the technological growth being made endogenous to the model. In this sense, the research sector is the foundation of the model, and its functioning is essential to both the model and the growth of the real economy.

3.4.1 From Designs to Production

Although an idea for a design can spring to anyone's mind at any particular moment, it is the systematic development of designs through dedicated individuals and institutions that forms the basis of the technological progress observed over the last several centuries. Preceding the industrial revolution and the subsequent and ongoing period of historically unparalleled economic growth was the Enlightenment. The establishment of dedicated institutions for scientific research as well as the spread of a positivist philosophy of the natural world laid the foundations for the rapid increase in productivity and industrialization (Mokyr, 2005). This can be conceived of as the emergence of the research sector of the economy.

At the core of the Enlightenment was the insight that the systematic study of the natural world could generate an understanding of its structure, as well as useful knowledge pertaining to economic activity. This notion of "useful knowledge" is an important feature of Mokyr's argument for the Enlightenment being a precondition for the industrial revolution (Mokyr, 2005).

The systematic conversion of scientific insights into economic production as described by Mokyr (2005) features as one of the three sectors of the economy as modelled by Romer. In his model, the intermediate-goods sector consumes designs from the research sector and in turn produces the producer durables used in the production of final goods (Romer 1990). Here follows a more detailed discussion of the research sector as described in the Romer-model.

3.4.2 Assumptions Underlying the Research Sector

Underlying equation (1) are five assumptions made by Romer. The first is that the research sector as a whole has access to the entirety of the existing stock of knowledge. This is justified by alluding to the nonrivalry of designs. In practice this means that each researcher employed in the sector has access to a certain portion of the total stock of knowledge, A_j. For reasons of mathematical conceptualization, this portion A_j should not be thought of as a percentage, but rather as an amount, as will be seen in section 5.4. Therefore the output of the individual researcher j is described by equation (2):

$$\dot{A}_j = \delta H_j A_j \tag{2}$$

(Romer, 1990)

The second assumption is that the production of designs can be increased in proportion to the amount of human capital dedicated to the sector. The third assumption is that the productivity of a worker in the research sector grows together with the existing stock of knowledge, the reason for this being that the worker has access to a growing supply of existing solutions to engineering problems. The last two assumptions constitute linearity in both the variable A and H_A. Romer clarifies that these are made mainly for practical reasons of analysis. Romer assumes that the marginal productivity of H_A must grow in tandem with A, as otherwise there would be a shift in the human capital employed in research to that employed in the intermediate and final goods sectors. The assumptions made of A and H_A are made in order to simplify the analysis of the model, and Romer clarifies that loosening them would not likely change the outcome, but rather add complexity on the way there. It should also be noted that the assumption that the research sector is relatively human-capital intensive has been taken to its extreme conclusion by excluding labor and capital from equation (1) all together (Romer, 1990).

The first three assumptions are most interesting in the context of this paper. The first of these is related to one of the variables in the proposed functions, while the second two are critiqued and augmented in research by Jones (1995).

Although the nonrivalry of designs enables the assumption that a researcher or engineer has access to the total stock of existing knowledge, there are many ways in which this assumption can be made untrue. Barriers to access can take both institutional and inadvertent forms. This fact forms the basis for the inclusion of openness in the proposed function for productivity.

The second and third assumptions, that the production of designs can increase in proportion to the amount of human capital dedicated to the sector, and that the productivity of a researcher or engineer grows with the total stock of knowledge, were problematized by Jones (1995). Jones argues that some of the predicted effects of Romer's model are inconsistent with empirical evidence from developed economies and proposes two main alterations to equation (1). The first is the addition of an exponent (ϕ) to the parameter A. Whether this exponent is greater than or less than 1 determines whether the size of the existing stock of knowledge is a hindrance to new designs or an advantage. The second is the addition of an exponent ($\boldsymbol{\lambda}$) to the parameter H_A, (denoted L_A by Jones), wherein $0 < \boldsymbol{\lambda} \leq 1$. This implies diminishing returns to the amount of human capital devoted to the research sector. This brings the theory more in line with the empirical data as presented by Jones, and also aligns with the increased risk of duplicated research as the research sector increases in size.

3.5 The parameter δ

The only variable in equation (1) that has not yet been problematized is the productivity parameter δ. In his outline of the model, Romer does not expand on it, and it is presented only as a given. As stated in section 1.1, the aim of this paper is to present various parameters which δ is likely to be a function of.

Given the importance of technological development for growth, and given the amount of investment into research and development, the question of research sector productivity is clearly an important one. By studying the variable δ it's possible to examine this important factor to economic growth without altering the dynamics of the Romer model. In examining variables potentially determining the value of δ, the general economic analysis of growth proposed by Romer can remain unchanged, while policy prescriptions for increased growth could be more accurately theorized.

There are some inherent limitations to measuring productivity in the research sector, largely relating to the idiosyncrasies related in section 3. Two common methods of measuring productivity in the research sector are research publication and patent rates. Both of these methods are relatively convenient as they are both quantifiable embodiments of the designs that the research sector produces. However, they both have their drawbacks.

A potential issue with using research publication data as an indicator of research productivity is that this measure struggles to account for differences in quality between publications. From a growth perspective some publications indicate an increase in knowledge with strong commercial potential, meaning that they have a higher impact from the perspective of the model. Other publications, while contributing to their field, might be considerably more difficult to convert into producer-durables, thereby having a smaller effect on growth.

At the same time, it's difficult to assess productivity per unit of time. For instance, a researcher or institution which publishes a significant number of findings over a given period, may not have produced many designs which can be used by the intermediate-goods sector. A counterpart might publish only once over the same period, however that particular design may have greater impact from a growth perspective. This implies that there would be a considerable lapse in time before the productivity of the two can be estimated, as the results of the research manifest themselves.

Support for this can be found in the fact that in the United States, while both the amount of resources devoted to research and the amount of academic articles published has increased markedly in the period 1970 to 2014, labor productivity increased by 1.6% per year in the same period. Compare this to the period 1920 to 1970, where productivity increased by 2.8% (Arora et al., 2019).

Another potential problem with using publishing data to indicate productivity in the research sector is the varying meaning behind authorship. A study by the Economist (2016) found that between 1996 and 2015, the average number of authors per published academic paper increased from 3.2 to 4.4. It's possible that some instances of co-authorship are reflective of increased pressure on researchers to publish a greater volume of research and less stringent definitions of authorship, rather than an increase in the actual amount of research being done (Baethge, 2008).

Patents may be a preferable measure to publications since they are more likely to represent the kinds of new knowledge that the intermediate-goods sector requires for production. A patented design is one which the originator finds worthy of making excludable and therefore is more likely to have potential commercial applications. However patents exist in a broader context than the one outlined above and can therefore also be a somewhat opaque indicator.

For example, there may exist considerable disparities in the standards applied in the patent granting process between countries and over time. For instance, the granting rate of patents has varied from between 80-90% in the UK and France to as low as 35% in Germany (Schankerman and Pakes, 1986). Griliches (1990) attributes these differences to procedural differences between patent-granting institutions and the resources available to them. This implies that there are significant differences in what conclusions can be drawn from patent data over time and between countries (Griliches, 1990).

In the last several decades, the number of applications to and patents granted by the US patent and Trademark Office (USPTO) has increased markedly. Much of this growth has been in digital sectors such as cloud computing, smartphones and software. The increase in the number of granted software patents was 60.2% between 2000 and 2013, while the number of applications increased by 168.6% in the same period (Webb et al., 2018). It should be noted that this data refers only to US patents, and is therefore likely skewed towards the composition of the US economy. This increase in the number of US patents should however be contrasted with evidence that over a similar period, research productivity in the United States seems to have fallen (Bloom et al., 2020).

It's possible that the increase in patents in software does indicate strong productivity in that particular sector, which does not preclude the possibility of declining productivity overall. However it's also possible that the patent data is not reflective of productivity, but rather may reflect other factors. For instance, it's possible that large, incumbent firms may use patenting as a method of threatening or engaging potential competitors with litigation in order to hinder their entrance to the market (Dinopoulos and Syropoulos, 2007). Evidence in support of this phenomenon has been found in the US biotechnology sector, where prospects of costly litigation has been found to have a discouraging effect on firms (Lerner, 1995).

The use of patents as an indicator of research productivity faces analogous difficulties to those of publication data. The problem of differentiating between scarcer, seminal and high-quality papers from the more common low-impact ones is paralleled in the variations in quality of patents. Some patents prove to be enormously influential, others have a diminutive impact from a growth and productivity perspective (Griliches, 1990).

What the measures above have in common is that they are both in some sense proxy measures. The designs and new knowledge that the research sector produces are not necessarily captured fully in these measures. Not all publications of research sit comfortably in Romer's definition or in the notion of "useful knowledge" as discussed by Mokyr. Not all patents reflect a novel design, but rather may reflect tactical legal posturing. However, the influence of patents on the market conditions of innovation make them an important factor in discussing the variable *market conditions* itself.

4. The Proposed Factors Underlying Productivity in Research

This section outlines each of the three proposed variables determining the productivity of the research sector, δ. Each variable is discussed in turn, with an introduction and a discussion of the reasons for their impact on δ.

The variables which this paper contends that Romer's research productivity parameter is a function of, are fairly broad and difficult to quantify. However this need not be a problem, for two reasons mainly. First, their purpose is to approximate some of the factors that do in fact determine productivity in the research sector. The potential, albeit inexact methods that could be used to quantify them ought perhaps to be used in combination with the measures outlined above in order to provide a fuller picture of the research sector.

The second thing to keep in mind is that the aim of this paper is to propose a path forward in furthering the Romer model. The model of economic growth proposed by Romer is just that, a model meant to theorize real-world processes. Similarly, the function of research productivity proposed here theorizes the factors which impact the productivity of the research sector as imagined by Romer. The difficulty of quantifying or estimating these factors does not preclude them from determining the δ parameter in Romer's model.

4.1 Variable 1, openness

Section 4.1.1 begins with a discussion of the nonrivalry of designs and the features of the research sector which are conducive to nonrivalry. These are features of the research sector which constitute *openness* and which have their basis in the historical development of research practices. *Openness*, together with the nonrivalry of designs enable agglomeration effects to occur uninhibited by geographical constraints. This aspect is discussed in section 4.1.2

4.1.1 Openness

As asserted earlier, designs have a sort of dual nature. On the one hand, their nonrivalry enables them to be the engines of economic growth. Once a design is produced, there is no limit to the number of potential users, nor to the number of potential derivative designs. On the other hand, in a so-called "marketplace of ideas", they have a degree of exclusivity granted to them through the patent system. These two characteristics can seem to be in contradiction with each other, and since the exclusivity of designs is a function of policy, there is a case for analyzing the policies that relate to fostering both nonrivalry in designs and their exclusivity.

One such way would be to differentiate between the settings in which designs are generated. The nonrivalry of designs is perhaps best utilized in an academic setting, whereas the ability to exclude others from profiting off of a design is more closely associated with the business sector. In terms of the model discussed in section 3.1, the nonrivalry of designs is most important in the research sector of the economy, while the excludability is most important to the intermediate goods sector.

Producing new designs for products and producer durables is essentially a creative endeavor. Despite the uniformity of the scientific method applied in research and development, at critical junctures in the process, someone must have a novel insight, which in turn leads to new experimentation. This creative aspect of the sector underscores the importance of research being conducted in institutions that are open to new ideas and capable of adapting to changing circumstances.

The development of standards for transparency and scientific practice during the 18th century has been described by Mokyr (2005) as important to the ascension of a growing, industrial economy. An increasing willingness to share insights and divulge the methods used to procure them characterized the emergence of a scientific "ethos" in the period of the Enlightenment. The use of common terms and categories in the publishing of research as well as an emergent norm of skepticism and verification reduced the access costs to the growing body of knowledge. Openness in research practices had the added benefit of reducing the risk of duplicative research and increasing knowledge spillovers. In total this enabled more people to either join the research sector or commercialize its findings (Mokyr, 2005).

It is these features of the research sector which constitute the variable *openness*. The degree to which they are prevalent impacts the productivity of the research sector.

4.2.2 Intra-institutional Collaborations and Agglomeration Effects

While it is difficult to quantify a notion as nebulous as “openness”, it's possible to conceive of certain measurable parameters which could be used to estimate the degree of openness in a particular institution or in the research sector of an economy. One such measure is the number of collaborations between institutions, such as university exchange programs, research collaborations across universities and countries, as well as partnerships between academia and the private sector. If the research institutions in an economy have many and well-developed partnerships and collaborations, there is greater opportunity for the pooling of resources and expertise, leading to a greater probability of coming up with new designs.

The importance of collaborations and partnerships between research institutions is closely related to network and agglomeration effects. There is strong evidence for the growth benefits of situating various parts of a supply chain in close proximity to each other, generating economies of agglomeration. The benefits of industry agglomeration are often connected to decreased transportation costs as the constituent parts of a supply chain are closer together, reducing logistical complexity. Another essential source of agglomeration benefits is knowledge spillovers. As different actors in a sector are situated closely together, interactions between knowledgeable workers become easier to facilitate and more common, leading to an increase in the sharing of information and insights, boosting innovation (Glaeser, 2010).

These kinds of effects have also been observed to be positively correlated with growth. Research done on joint research projects in Europe has found that institutionalized collaborations between researchers can be beneficial for those at the center of a knowledge network as well as for those at the periphery (Meliciani, Di Cagno, Fabrizi & Marini, 2021).

Since designs as input products for the intermediate goods sector do not necessarily need to be physically embodied, geographical circumstances do not limit the opportunities for achieving agglomeration effects as much as they do for other sectors. An example of this is the coding platform Github, whose purpose is partly to facilitate knowledge sharing between coders. The platform enables users to upload and discuss code, creating a common resource which coders can use in their work (Github, 2023). Github and other platforms like it thus constitute an example of agglomeration effects not constrained by geography, utilizing the communicability and nonrivalry of designs .

4.2 Variable 2, The Market Conditions for Research

Section 4.2 outlines three aspects of the second proposed variable, *market conditions* for research. The question here, as outlined in the introduction, is what market conditions are most advantageous for the productivity of the research sector. The first aspect is the potential benefit of a market for designs characterized by low market concentration and a high degree of competition. The second is the argument for a market for designs characterized by greater scale and market concentration with larger institutions. Finally the role of financial markets and institutions for funding the research sector is discussed.

A key premise of Romer's model is that the technological change which underpins growth comes about from actors responding to market incentives. Each of the three sectors of the economy outlined in section 3.1 correspond to this notion. The final-goods sector produces goods for consumers, while in turn consuming the producer durables sold by the intermediate-goods sector. The research sector sells designs to the intermediate-goods sector.

Seeing as market incentives form the basis of technological growth, it stands to reason that the market conditions in which research takes place would have a large impact on the kind and volume of designs produced and thereby productivity. At the most basic level, the general economic conditions of a society are likely to play a large role in whether sustained economic growth is likely to occur at all. A society which does not provide incentives for technological innovation is likely to struggle to generate the kind of technological development necessary for growth (Baumol, 1990).

As there may be an intuitive argument that as economic competition fosters innovation and incentivises productivity growth in the economy generally, it's reasonable to assume that the same ought to hold true for the research sector. On the other hand, there are instances where a sufficiently large market actor can harness economies of scale to provide greater welfare for consumers. The question is then, whether productive research is more likely to be conducted in a market characterized by smaller scale and greater competition, or in a market characterized by larger, institutional actors capable of providing scale and long term stability.

4.2.1 Competition and Innovation

The effect of market concentration on the productivity of research stems from the difference in imperatives faced by an incumbent firm with a profitable market position and a firm aspiring to enter a market. In order to defend its market position, the incumbent firm must either innovate to stay ahead of its competitors or expend resources hindering them from competing effectively. The entrant firm however must innovate in order to bring new products to the market. It is also less likely to possess the financial resources to engage in costly litigation.

It should be remembered that the essential function of the patent system is to bestow on an inventor a legal monopoly on the design in question and to enable legal measures against others trying to make a profit off the patented design. However there is likely a point at which the strategic use of patenting becomes an inefficient use of resources from the perspective of the production of new designs. Evidence for this phenomenon comes from Lerner who found that the total amount spent on patent litigation in 1991 came out to more than 25% of firms' expenditure on basic research (Lerner, 1995).

Cohen, Nelson and Walsh (2000), find evidence that the practice of patenting not to monopolize a design, but rather to stymie the ability of others to innovate in proximity is not uncommon. For example, firms may employ a “fencing strategy” wherein patents for technologies which may substitute the firm's product are applied for in order to deny others the ability to compete with these technologies. The effect is that certain technologies are fenced off from the market. The owner of the patent may not intend ever to commercialize the technology, but rather seeks only to prevent its use by others (Cohen, Nelson & Walsh, 2000). This way a firm may protect its own market position while stymying the development of derivative technologies, closing down avenues of technological development.

Another method described is to patent complementary technologies. This is more useful for complex products with several interdependent technologies. By patenting technologies adjacent to its own product, a firm may ensure itself of the right to exclude others from the market or the right to license the technology to other firms, generating a rent (Cohen et al., 2002). This may not have as strong an impact on the research sector itself so much as creating inefficiencies in the final-goods sector. However it's not unlikely that the widespread use of this tactic would have a discouraging effect on innovation.

While it's conceivable for firms of any size to engage in these practices, it is incumbent firms with market positions to defend which have the strongest incentives and ability to do so. In order to pursue a patent blocking strategy, a firm must have the means to credibly threaten litigation. The threat of being embroiled in a legal dispute is more potent against a fledgling firm seeking to enter the market. Therefore there is reason to believe that the effect of a market characterized by powerful incumbent firms will have a negative impact on the overall productivity of the research sector.

4.2.2 Corporate Research and innovation

While there is reason to believe that firms with strong positions in the market may exploit their status in order to hinder innovation in their fields, it is also possible that the absence of firms conducting ambitious and wide research projects has a comparably negative impact on the productivity of the research sector. Two main reasons for this are corporate research's inclination towards multidisciplinarity and mission oriented research. Here, corporate research is taken to mean research conducted by large, established firms. Firms such as these are often active in several markets. Typical examples include American firms such as Intel, General Electric and DuPont chemicals, or such Japanese firms as Mitsubishi or Toshiba.

In recent years the landscape of innovation and the research sector has shifted, at least in the United States. There has been a general shift from research conducted and applied in a corporate setting to research being conducted by universities and commercialized through startups and technology acquisitions. This shift has largely coincided with a general decline in US productivity growth (Arora et al., 2019).

There are several reasons to believe that large corporations are well suited to conduct the kind of research which generates growth in productivity, and therefore economic growth more generally. Part of the explanation is the nature of the research conducted in a corporate setting and part is the nature of the corporate research setting itself.

As asserted earlier, not all research and not all new designs are equal from the perspective of economic growth. This is further underlined by the structure of Romer's model of the economy. The research sector encompasses all research done and does not differentiate between advancements with many practical applications and those with purely theoretical ramifications. An exaggerated example of this would be the difference between research conducted by an art history department and that conducted in an applied chemistry laboratory. While the advances in the social sciences undoubtedly have great social value and potentially commercial value, it seems likely that research oriented towards solving practical problems has a higher probability of generating designs of great value to the intermediate and final-goods sectors.

Research conducted by large corporations is likely to fall in between hyper-specialized research with limited applications and broad basic research with a considerable distance to commercialization. The reason for this is that the essential purpose of corporate research is to generate commercial opportunities and profits for the firm. Therefore the research will tend to be considerably more focused on providing solutions to practical problems and exploring technology with clear commercial potential. At the same time, a large corporation with a strong market position can provide researchers with greater flexibility and a longer time-frame than a smaller firm seeking to cement a place in the market (Arora et al., 2019).

The ability of a large firm conducting research in-house to provide longer time frames and greater leeway to researchers also relates to the kind of research a corporation is able and likely to produce. One reason for this may be the relative prevalence of multidisciplinarity in corporate research. Virtually no product is the result of only one technological process or scientific insight. While university research is more likely to be aimed at producing a singular insight per project, the object of corporate research is to produce insights intended for use in concert with many others in a product. For this reason a corporate research facility is more likely to make use of expertise from a wide variety of disciplines in order to fuse them into a greater whole. Evidence for this can be found in the fact that in technologically advanced fields, corporate research tends on average to have more authors per paper than non-corporate research (Arora et al., 2019). This multidisciplinarity may yield a higher productivity for the conducted research.

Nelson (1959) argues that a firm with a narrow technological focus and product range is unlikely to capture a large share of the social value created by new insights. This is due to their limited opportunities for practically applying such an insight. By contrast, a larger firm with a broader commercial outlook and wider technological base will capture a larger share of the benefits of basic research conducted within the firm. The results of basic research conducted by the firm is more likely to find a wider set of applications within the firm's operations. His example is that of large chemical companies using a vast variety of chemical processes in their wide range of product offerings (Nelson, 1959).

4.2.3 The Role of Financial Markets

According to Arora et al. (2019), the current system of US innovation has partly come about as the result of reforms to policy on intellectual property produced through federally funded research as well as a relaxing of the antitrust regulatory environment. The Bayhe-Dole act passed by the US Congress in 1980 granted ownership and licensing rights to research results to the universities that produced them, incentivizing researchers and universities to commercialize their findings. This together with increased leeway on mergers and acquisitions from regulators and a liberalization of financial markets formed the current innovation paradigm of university startups and venture-capital funding (Arora et al., 2019).

In some sense this system may be considered more dynamic and agile than a system structured around corporate research, since the institutions involved are generally smaller and more specialized. However a venture capital funding structure may bring with it other drawbacks than those outlined in section 4.3.2.

The process of change from a corporate based system of innovation to a venture capital based system broadly coincides with a period of falling interest rates across developed economies.

Federal Reserve Economic Data (FRED) reports that from a peak of 19.1% in June of 1981, the federal funds effective rate has trended largely downwards, bottoming out and staying at near zero in the 2010's (FRED, 2023). In short, the current system of venture capital based innovation is as yet untested in a macroeconomic environment not characterized by historically low interest rates.

The present question is then, what role does this shift in the funding practices of the research sector play in the broader impact of *market conditions* on the productivity of the sector? If fluctuations in interest rates cause volatility in the amount of capital available to the research sector, this need not impact productivity per se. An increase or decrease in capital available to the research sector would naturally have an impact on the amount of research which is in fact produced over a period, however the productivity of the research which takes place over that period is not a function of the amount of financing.

It is however conceivable that increased volatility in the amount of available capital for the research sector would have an indirect impact on the productivity of the sector. Exposure to fluctuations in interest rates increases uncertainty about what kind of funding is available for research projects and when. In the face of rapidly changing macroeconomic conditions, a venture capital funded research project may find itself under increased pressure to produce revenue or to secure the likelihood of successful results.

This potential for volatility in the timeframes and expectations for individual research projects is likely to have a negative impact on the productivity of the sector as a whole. Uncertainty of this kind may place a premium on designs building on proven technologies which are likely quicker to bring to market. Fluctuations in interest rates and the subsequent uncertainty regarding timeframes and expectations may thus be to the detriment of more long term or unorthodox projects, which carry with them increased investor risk.

By contrast, research conducted within a corporation is to a greater extent shielded from the fluctuations of financial markets, as corporate funding is likely more dependent on the firm's revenues than on borrowing rates. The same reasoning holds for publicly funded research taking place in universities.

Thus, there is reason to believe that venture capital funded research is more exposed to rapid changes in the circumstances surrounding financing than either corporate or publicly funded research. This exposure to market fluctuations introduces greater uncertainty in the decision making process for this kind of research, reducing incentives for sustained risk-taking and very long term projects, thus negatively impacting the productivity of the research sector.

4.2.4 The Interplay Between the Research and Intermediate-goods Sectors

The counterbalancing drawbacks and benefits of the forces discussed in section 4. implies the theoretical existence of optimal market conditions seen from the perspective of the research sector. It's clear that a market which is unable to sustain long term or unorthodox research as problems of scale and competition hinder ambitious projects is not conducive to research productivity. At the same time, a market characterized by concentration among a few large firms relatively shielded from competition is likely to result in a misallocation of resources towards protecting profits and market positions and away from innovative research.

Another implication of the arguments above is the need for the current "model" of innovation prevalent in many advanced economies to be either adapted or further developed to account for the apparent current dearth of productive innovation found by Bloom et al. (2020).

Joel Mokyr (2005) underlines the importance of institutionalizing the transfer of knowledge from those who produced it to those who could put it into productive use. Historically there has been a considerable social gap between the learned classes and those engaged in productive economic activity. This began to change during the 18th century, leading to a more rapid conversion of scientific insight into economic production (Mokyr, 2005).

This issue of communication between the originators of scientific insights and their agents of commercialization, and the resultant growth is raised in a modern context by Arora et al. as referenced in section 4.2.2. The conclusion of that paper is that the challenge facing the US system of innovation, and by extension advanced economies generally, is to better facilitate this communication. The current norm of university research being commercialized through startups largely dependent on VC-funding faces the challenge of bridging the considerable gap between academic research and its commercialization (Arora et al., 2019).

From the perspective of the model discussed here, this question is one of transferring the production of the research sector to the intermediate-goods sector. On the face of it, this relationship between the economic sectors of Romer's model is not directly related to the productivity of the research sector. However it may indirectly have an impact on the parameter which we are concerned with, the research sector's productivity.

If, as argued in section 4.1, there are qualitative differences between research projects and their results, it stands to reason that the working relationship between the research and intermediate-goods sectors would have an impact on the character of research produced. A research sector which is to a large degree integrated with the intermediate-goods sector which it supplies is likely to be more finely attuned to the needs of this sector. Therefore it's more likely to produce research which is more immediately applicable to the problems faced by the intermediate-goods sector, which is in turn attuned to demand generated by the final-goods sector. Conversely, a research sector which is largely disconnected from the intermediate-goods sector is on the whole more likely to result in a larger share of produced designs and insights with limited immediate commercial applicability.

This issue of the closeness of the intermediate-goods sector and the research sector is discussed by Romer as he points out that it's not uncommon for a firm to be active in both the research and intermediate-goods sectors simultaneously (Romer, 1990). It is this state of affairs which concurs with the notion of corporate research above.

4.2.5 Aggregate Effect of Market Conditions

One of the three premises which Romer states as the conditions underlying his model of growth is that innovation takes place in response to market incentives. It is the relationship between the intermediate-goods sector and the research sector which shapes the kind of research for which there are strong incentives. For this reason, the *market conditions* in which research takes place likely play an important role in determining how productive the research sector is.

A market for designs characterized by smaller actors, uncertainty and problems of scale is likely to struggle with long-term, high risk research, in a way in which strong institutional actors are less likely to. At the same time, a high degree of market concentration reduces competition, creating incentives to guard existing profits as opposed to disrupting the market with new designs. The level of uncertainty faced by research institutions is also likely to affect the kinds of research projects which are feasible, thereby affecting the productivity of the sector as a whole.

4.3 Variable 3, Access to the Stock of Knowledge

The third variable in the proposed function is the practical *accessibility of knowledge* to the individual researcher. The degree to which an individual researcher is able to make productive use of knowledge available may vary over time, with effects on the productivity of the research sector as a whole.

Central to the working of Romer's equation for the production of new knowledge is the parameter A. It represents an index of the current stock of knowledge. The model is premised on the assumption that those involved in research have access to the entirety of the total stock of knowledge. The assumption is theoretically feasible by virtue of the nonrivalry of designs. For the individual researcher *j*, possessing a level of human capital H_j and with access to a portion of the total stock of knowledge, A_j, his production of new designs is expressed in equation (2). Romer then expands this notion to encompass the research sector as a whole, giving us equation (1). This is achieved through basing the equilibrium of the model on the assumption that all researchers have access to the total stock of knowledge (A_j=A). In this case the output of the individual researcher *j* is also illustrated by equation (1) (Romer, 1990).

However the same result can be reached through the aggregate of all researchers. If each researcher has access to a portion of A, equal to A_j, the total number of individual researchers together have access to the total stock of knowledge.

The assumption that A_j could be thought of as equal to A is, while theoretically feasible due to the nonrivalry of designs, somewhat unrealistic. It seems reasonable to assume that the ability of an individual researcher to have access to the total stock of knowledge is somewhat limited. However, the argument above enables us to analyze the role of the portion of knowledge A_j and its effect on research productivity. This corresponds to the variable in question, *access to knowledge,* since A_j is an expression of the access which the individual researcher has. By extension, it also says something about the way in which the research sector in aggregate has access to the total stock of knowledge.

It is through the notion of portions of knowledge that the variable *access to knowledge* is derived. The portion A_j which a researcher has access to is his degree of access to the total stock of knowledge. It stands to reason that the larger the value of A_j, the more productive the individual researcher ought to be, just as we assume that a greater level of human capital also has a positive effect on the researcher's productivity.

For our purposes however, the above line of reasoning regarding the parameter A can usefully be folded into the productivity parameter δ, being our current object of inquiry. Essentially, the assumptions made with regard to A are maintained, thereby maintaining the dynamics of the model, while the degree of limitations on the ability of the individual researcher to make use of the knowledge they have access to is shown through the variable *access to knowledge*, folded into δ. Meaning that while the degree of access to existing knowledge brings the research sector to a certain level of production, the question of how much use is able to be made of said access is dependent on the productivity variable.

The degree of access to the existing stock of knowledge is conceived of in two ways here. The first is the degree to which Romer’s assumption overlaps with the real world. Although great strides have been made in reducing access costs to advanced technology, it seems reasonable to assume that some barriers persist. Some of these barriers may pertain to other functions of the research sector, such as proprietary knowledge and industry secrets, both of which serve an analogous function to the patent system (Romer, 1990).

The second way to think about *access to knowledge* is to relate it to how this access can be converted into research production. The problem here is that while an individual may have access to a certain amount of information, this does not imply that it is all comprehensible to him. More generally it could be argued that while the total stock of knowledge has expanded rapidly together with falling access costs, it's possible that effective systems for the categorization and conveying of information have not kept up with these developments.

The difference between simple access to knowledge and the ability to make practical use of it can be illustrated by the following example. Two individual researchers may be granted access to identical bodies of information pertaining to a given issue. In this sense they both have the same amount of access to the information in question. However if one researcher receives the material printed out and placed at random in a great number of containers, while the other receives a searchable database organized by keywords, titles, authors, etc. it's clear that their degree of access is in some sense no longer equivalent. The researcher with access to the categorized database is very likely to exhibit higher productivity than his colleague inundated with uncategorized material.

4.3.1 The Distribution of Knowledge

Romer's assumption that the research sector as a whole has access to the total stock of knowledge A, is a sound one. Sound on the theoretical basis that knowledge is nonrivalrous, as well as the intuitive notion that the entirety of the sector devoted to producing knowledge ought together to have access to the entirety of the knowledge produced. This holds also for the concept of the individual researcher *j* having access to a portion of the total stock of knowledge, A_j.

However research production is not dependent merely on access to knowledge, but rather is also constricted by the individual researcher's capacity to internalize and make use of the knowledge available, as described in section 3.4. It is largely this argument which lies behind the addition of the exponent ϕ to A in equation (1) by C. Jones (1995). Similarly, the marginal returns of H_j are also thought to be diminishing, as each additional year spent accumulating human capital is one not spent in the production of new knowledge[1].

The notion of whether or not a researcher or inventor has the means to make use of knowledge in the production of new designs is an important one since it acts as a qualification of Romer's assumption on full access to the stock of knowledge. The reduction of barriers to accessing and making use of scientific insights in innovation is central to the size of the portion of the total amount of knowledge available to the individual researcher (A_j).

Jones addition of the exponent ϕ to the parameter A reflects the question of whether the existing body of knowledge is a net positive influence on the production of new knowledge, or whether it makes finding new insights more difficult. A value of $\phi > 0$ means that the parameter A has a positive effect on research production while $\phi < 0$ implies that an increasing stock of knowledge makes increases the difficulty of acquiring new knowledge. A negative value of ϕ corresponds to a state of affairs described as "fishing out", wherein the growing body of knowledge increases the difficulty of attaining new insights (Jones, 1995).

Time series evidence of falling research productivity from Bloom et al. (2020), indicates that $0 < \phi < 1$. Another expression of their findings is that it would require a doubling of research effort every 13 years in order to maintain a constant growth in GDP per capita (Bloom et al., 2020). These findings suggest diminishing returns on the total stock of knowledge, a case corresponding to $0 < \phi < 1$.

An argument for research productivity declining as the value of A grows, is that the larger the total stock of knowledge is, the greater effort and time it takes for a researcher to reach a level of education and understanding commensurate with increasing the total stock of knowledge. As the prevailing level of technology becomes more complex it becomes increasingly difficult for an individual researcher to attain a wide enough understanding of the various insights and techniques required to synthesize them into new designs. A consequence of this is a greater degree of research specialization and an increase in team-based efforts in research (Jones, 2009).

Naturally, this argument can be developed by factoring in the fact that it is not always possible to categorically differentiate between an individual acquiring advanced human capital, and engaging in the production of new knowledge simultaneously.

In support of this claim are two findings. The first being that the average age at which doctoral degrees are attained has been steadily increasing since the 1960s and that the average age of Nobel Prize winners has been increasing in a similar manner (Jones, 2009). The second finding is that since the middle of the 20th century the amount of research published and patented by teams of researchers increasingly outnumber that done by individuals (Wuchty, Jones & Uzzi, 2007).

Together these findings indicate that the productivity of the individual researcher is declining over time, possibly as a function of the increasing total stock of knowledge. As total knowledge accumulates, it becomes increasingly difficult to maintain the size of A_j, that is the proportion of A which the individual researcher *j* has access to. In this sense it's possible that an individual researcher, due to changes in the variable *openness* for example, may gain access to a substantially larger amount of information, while his portion of the total (A) has shrunk.

However the implication does not necessarily apply to the productivity of the research sector as a whole. Although the portion of knowledge accessible and intelligible to the individual researcher may decrease as the total sum of knowledge increases, the assumption that the research sector as a whole has access to the entirety of the stock of knowledge still holds. The productivity of the sector is thus contingent on combining an increasing number of smaller portions of knowledge into a whole in order to produce new designs. New designs necessarily being the product of a wider range of individual inputs might go some way to explain the upward trend in the number of authors per paper found by Wuchty, Jones and Uzzi (2007).

4.3.2 Categorizing Knowledge

In this section, the notion of organizing knowledge and increasing ease of access is discussed. If the arguments in section 4.3.1 hold true, the implication is that the productivity of the research sector is dependent on its ability to coordinate the knowledge and efforts of an increasing number of increasingly specialized researchers. As the remit of the individual researcher or inventor shrinks as knowledge is accumulated, the ability to coordinate the work and insights of many researchers becomes increasingly important in determining the productivity of research.

It also implies that as the total stock of knowledge increases, methods for navigating through the repository of human knowledge ought to be developed and improved upon in tandem with the growing stock of knowledge. By improving the ability of the individual researcher to sift through vast amounts of material and identify the information necessary to innovate, the effect of the shrinking portion of knowledge available to the individual can be counteracted.

Alternatively, the practical use of the *access to knowledge* assumed in the Romer model will decrease as more knowledge is accumulated. Without commensurate capacity to navigate research material, each researcher finds themselves under a deluge of information. It is this state of affairs which most closely compares to Jones' analysis of the ever receding frontier of knowledge, and the subsequent decline of research productivity (Jones, 2009).

The importance of organizing and navigating through a rapidly growing body of knowledge is visible in the early development of what can be called a dedicated research sector during the Enlightenment and early industrial revolution. A key component of the spread of the scientific mindset was the development of a systematic approach to cataloging knowledge. By cataloging results and attempting to distill them into general principles, researchers of the 18th century enabled systematic attempts at falsification and verification. One approach to this systematization was the increased use of mathematics as a way of communicating precisely and over language barriers (Mokyr, 2005).

Another example of innovation in the way knowledge was conveyed was the novel use of graphic aids. Throughout the 18th century there was an increased use of tables as a means of categorizing increasingly detailed data in a way that was more readily comprehensible to readers (Heilborne, 1990). Major advances in the use of graphs have also been described as essential to the modern language of science and research. Individual innovators such as William Playfair made enormous strides in the development of graphs as a method of communicating complex datasets (Costigan-Eaves & McDonald-Ross, 1990).

Developments such as these constitute innovations in the *accessibility of knowledge*, as they enabled greater ease of navigation through large tracts of information. It's possible that the decline in research productivity observed by Bloom et al. (2009) can be attributed to a mismatch between the pace at which the stock of knowledge has grown and the individual researcher's ability to navigate through the increasing amount of information available.

The final variable in the proposed function is then the degree to which the individual researcher can make use of the knowledge made available. This implies that the value of the portion of the total stock of knowledge available to the individual researcher, A_j is in turn contingent on the methods available to the researcher in navigating this knowledge effectively.

For the research sector as a whole, this has implications for the possibility of efficient collaboration between large groups of researchers. As has been observed, the number of authors per paper has been steadily increasing over the last several decades (Wuchty, Jones & Uzzi, 2007). Simultaneously, there has been an increased tendency towards specialized university research in lieu of more commercially oriented corporate research, at least in the United States (Arora et al., 2019). Taken together, these facts imply that collaborative research has been increasing in importance and is likely to continue to outpace designs made by individual inventors. In light of this, the ability of the research sector to efficiently convey relevant information between a large and disparate community of specialists would seem to play an important role in the productivity of the research sector as a whole.

5. Mathematical Characteristics of the Three Variables

This section describes the potential mathematical characteristics of each variable and discusses how they might interact with each other in a function describing the productivity of the research sector.

5.1 Mathematical Expression

Equation (3) is an example of what the function of δ could look like. There are likely ways to express this relationship more elegantly, however in this case the equation serves as a representation of the mathematical relationships between the three variables. In sections 5.2-5.4, the characteristics of each variable is discussed in more detail.

$$\delta = f(x_1, x_2, x_3) = x_1^a (g(x_2)) x_3^b \; ; \qquad (3)$$

$$0 < a < 1; 0 < b < 1; \textit{wherein } g(x_2) \textit{ is a concave function}$$

$$x_1 = openness; \; x_2 = Market\ Conditions; \; x_3 = \left(\frac{A_j}{A} * 100\right) = Access\ to\ Knowledge$$

Here, each variable is multiplied with the others, accounting for the fact that a value of zero for any of them would reduce research productivity to zero as well. The exponents *a* and *b* are both greater than zero and less than one, denoting the diminishing returns of both *openness* and *access to knowledge*. *Market conditions*, x_1 exhibit the character of a concave function, accounting for the existence of an optimum value.

5.2 Variable 1, Diminishing Returns to Openness

The variable *openness* is likely best characterized as a multiplicative variable with a fractional exponent. Being multiplicative reflects the fact that a completely closed research sector in practice negates the third premise of Romer's (1990) model. This premise being the nonrivalry of designs. A closed research sector characterized by secrecy, a resistance to sharing knowledge, and to new modes of thought prevents the nonrivalry of designs from taking effect. Therefore it makes sense that a value of zero for the variable *openness* would entail a value of the productivity parameter also equal to zero.

A fractional exponent reflects the naturally diminishing marginal returns of *openness*. It seems likely that the increase in research productivity brought about by a research sector increasingly “open” would flatten out after a certain point. This point being one at which institutional limits on the nonrivalry of designs are essentially eliminated. Once the practices of transparency, common methods of communication, the explanation of methods and so forth are in place, it becomes increasingly difficult to conceive of ways to increase *openness*. Those increases which could occur would consequently have less of an impact on the productivity of the sector as a whole. Therefore mathematical expression of the variable *openness* would have an exponent larger than zero, less than one, indicating these diminishing returns.

5.3 Variable 2, Optimum Market Conditions

One of the three premises on which the Romer-model is predicated, is that innovation takes place in a market, with actors responding to economic incentives (Romer, 1990). As discussed in section 4.2, several characteristics of a market for designs which can be beneficial to the productivity of the research sector, are not necessarily a positive influence in all cases.

For example, a patent system conveying legal monopolies on designs seems essential to creating those economic incentives which drive the production of new designs. The patent system provides designs with their excludability, enabling the market. However, as findings by Lerner (1995) and Dinopoulos and Syropoulos (2007) indicate, the patent system can also work against a productive research sector, if incumbent firms use it to fend off potential competition.

A similar dynamic can be observed in the benefits and drawbacks of greater competition, with smaller firms and actors involved. As detailed by Arora et al. (2019), in-house corporate research may have advantages over smaller firms from a productivity perspective, thanks to greater scale and resources. In comparing corporate research and publicly funded university research, Arora et al. (2019) also find a tradeoff between opportunities for greater specialization and long term projects in academia and the multidisciplinarity and commercial focus of corporate research.

Finally, the impact of the funding structure of research constitutes a weighing of the more rapid and flexible capital allocation provided by venture capital, and more stable long term funding from larger firms and universities.

In all these cases, the role of *market conditions* in determining the productivity of the research sector entail a form of optimization. The patent system enabling designs to be made excludable creates incentives for the research sector, provided that incumbent firms are not dominant enough to use the patent system to prevent the emergence of competitive designs. Inversely, low degrees of market concentration risk reducing the opportunities for larger scale, multidisciplinary research with a strong commercial orientation.

In determining the potential mathematical characteristics of this variable, the above reasoning implies that an optimal value of the variable could be found. Graphically, the impact of the variable *market conditions* could be described as a concave function, where increasing or decreasing market concentration improves research productivity up until the function's maximum point, after which productivity is impacted negatively. The commonly used Herfindahl-Hirschman index of market concentration may be a means of calculating a proxy of this value. The Herfindahl-Hirschman index measures market concentration by taking the square of each firm's market share denoted ms_i (as a percentage) and summing them together, creating a value indicating the level of market concentration (Rhoades, 1993). Rhoades expresses this as follows:

$$HHI = \sum_{i=1}^{n} (ms_i)^2 \qquad (4)$$

How this variable would interact with the other two is another question. The existence of a market for designs being one of the three premises for Romer’s model of growth implies that the variable *market conditions* ought to be a multiplicative one. At minimum, the value must be greater than zero for the research sector to exhibit any productivity. Without the existence of a market, Romer’s premise fails and incentives to produce new designs are absent.

Visually, the effect of *market conditions* on research productivity (δ), would as mentioned be a concave function. A stylized illustration of this can be found in *figure 1*. Mathematically, one can say that simply say that *market conditions* (x_2), is expressed through the function $g(x_2)$ where g is a concave function.

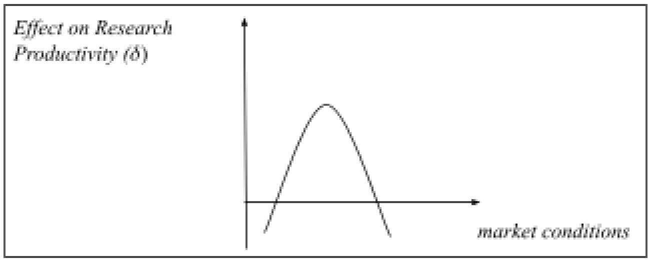

Figure 1.

5.4 Variable 3, Multiplicative Effect of Access to The Stock of Knowledge

The mathematical characteristics of variable 3 seem likely to be broadly similar to those of the variable *openness*. Both can be conceived of as multiplicative with a fractional exponent.

That *access to the stock of knowledge* should be multiplicative follows from the same reasoning as behind *openness* and *market conditions* being multiplicative. A research sector which has no access to the stock of knowledge is essentially nonproductive. The effect of designs being nonrivalrous largely expresses itself in the assumption that researchers have access to previous designs, characterized as the total stock of existing knowledge. If this access is zero, then there can be no accumulation of knowledge and development of derivative designs from successful ones. In a sense, this would entail a society without memory, unable to transfer knowledge from one person to another. For this reason, the variable should be thought of as multiplicative. If the variable is equal to zero, the productivity would also be equal to zero.

Access to the stock of knowledge differs however from the variable *openness* in the degree to which returns are likely to be diminishing. If the *accessibility of knowledge* is able to grow in concert with the total stock of knowledge, then the positive effect on productivity would be a linear one. Equation (2) shows that the total stock of knowledge, which Romer assumes there is full access to, is a multiplicative variable in the equation. However, as argued in section 4.3, if the means of navigating and accessing the total stock of knowledge does not develop in tandem with the total stock of knowledge, then formal access gradually becomes less meaningful.

This line of reasoning implies a simple multiplicative variable with an exponent equal to one. In theory however, similar causes for diminishing returns apply to the *accessibility of knowledge* as to *openness*. Theoretically, the level of *accessibility of knowledge* such that the portion of knowledge available to the individual researcher (A_j, described in section 4.3) is equal to the total stock of knowledge ($A_j = A$), this would constitute an upper limit to the impact of the variable accessibility. This state of affairs is described as an assumption for the equilibrium of the Romer (1990) model, and is discussed in more detail in section 4.3. This limit could be conceived of as the limits of the researcher's creativity, as his productivity and that of the sector as a whole would at this point be decided by the rate at which ideas for new designs occur .

If the mathematical expression for the third variable were to account for this purely theoretical scenario, the exponent could not be equal to one but rather would be less than one. Albeit very close to being equal to one.

It's important to note that the variable *access to knowledge* is not equal to A_j, since this would entail that variable featuring in equation (2) twice. Instead, *access to knowledge* is A_j expressed as a *proportion* of A. Therefore the variable *access to knowledge* can be expressed as:

$$x_3 = \left(\frac{A_j}{A} * 100\right)^b \tag{5}$$

Multiplying the quotient $\frac{A_j}{A}$ by 100, changes the value of the variable from being less than one, to greater than one. If this were not done, $\frac{A_j}{A}$ would have a value of 0.2 (corresponding to 20%) for instance. Were this to be given the exponent *b* and multiplied with the other two variables, it would reduce the value of δ, which is not the desired effect. By multiplying the quotient with 100, a given value of say, 0.2, becomes a value of 20. This way, an increase in the variable corresponds to an increase in δ.

6. Conclusion

6.1 Summary

The aim of this thesis has been to inquire into a few of the factors which may underpin the productivity of the research sector, as defined in Romers (1990) model of economic growth. Theoretically, productivity in a creative industry such as research is a function of innumerable factors, with three potential ones singled out for examination here. These three factors are *openness, market conditions,* and *access to the stock of knowledge*. They all stem from the assumptions and premises on which Romer's model is based.

The variable *openness* stems from the nonrivalrous nature of designs as described by Romer. Since the cost of replicating and communicating an idea, or in this case a design, is essentially zero, the design can in some sense be thought of as a public good. It is this characteristic which, according to Romer, is fundamental to the nature of technology and thereby technological development. The application of this characteristic is expressed through the *openness* of the research sector which produces designs. Research practices characterized by openness to new information, low barriers to entry and transparency exploit the nonrival character of designs to a greater degree. For this reason, the *openness* of the research sector is thought to have an impact on the productivity of the sector as a whole.

Market conditions as the second variable stems from Romer's second premise, that technological change occurs as a result of economic incentives. *Market conditions* determine the environment in which research takes place, and impacts the incentives that drive innovation. A major aspect of the market for designs is the ability of firms and institutions to exclude others from new designs, and secure welfare for themselves.

There are good reasons to believe that a market for designs characterized by strong competition and specialized institutions are positive for productivity. At the same time however, it's possible that if the market concentration is too low, advantages associated with corporate research such as multidisciplinarity and commercial orientation are missed, resulting in lower productivity.

The third variable, *access to the stock of knowledge* is based on the value of A_j or the portion of the total stock of knowledge which the individual researcher has access to. The size of A_j changes with the size of the total stock of knowledge (A). If A_j were to shrink in proportion to A, the necessity of collaboration between researchers increases. A larger total stock of knowledge also requires better means of categorizing and navigating through it in order for productivity not to decrease. Developing the systems of access, essentially means of navigating a growing body of knowledge, is necessary to maintain a certain level of productivity. The degree to which an individual researcher or research team is able to make use of the amount of knowledge they have access to, thus likely impacts their overall productivity and by extension, the productivity of the research sector as a whole.

If one were to place the three variables together in a function illustrating the productivity of the research sector, all three would be multiplicative. This would serve to illustrate that some value of all three is essential to a functioning research sector. The variables *openness* and *access to knowledge* would both exhibit diminishing returns through a fractional exponent, reflecting the fact that the impact of these variables after a certain point is likely to be diminishing. The reasoning in section 5.3 implies that *market conditions* is a variable with an optimal value, which does not exhibit a uniformly positive effect.

6.2 Limitations

The main limiting factor of this paper is the absence of empirical data to test the theory, together with the limited scope of the underlying literature. Although some potential sources of empirics are mentioned, their inclusion in the paper may have opened up further avenues of inquiry.

Another potential limitation is the dependence on evidence from the United States. This limits the applicability of any conclusions drawn, as they do not necessarily hold for other economies which may have other circumstances to consider. However the size of the United States economy and its role in the development of many advanced technologies goes some way in offsetting this limitation. Furthermore, the degree of internationalization which prevails in the research sectors of advanced economies today imply that conclusions drawn from the US are not unlikely to hold for other countries as well.

6.3 Potential Avenues for Future Research

There are many potential avenues for further research based on the questions raised in these pages. Perhaps the clearest one would be an inquiry into other variables which play a part in determining the productivity of the research sector. As stated earlier, the three variables discussed in this essay by no means constitute an exhaustive list, but rather are three candidates for further study. The three discussed variables are likely themselves functions of further factors, and these too would make an interesting object of study.

Another question raised would be how these variables could be measured empirically. If the variables themselves or an appropriate proxy could be given an estimated value, the weight of the variable in determining research productivity could be determined. Alternatively, a variable could be discarded if found not to have a significant effect on the productivity parameter.

A different disciplinary framework may also yield interesting results. The theoretical framework used in this paper has been an economic one, as economic growth sits firmly within this discipline. However, given the nature of growth and of knowledge, it's possible that other angles of approach and analytical frameworks might be beneficial to consider.

For example, the index level of technology and the accumulation of knowledge are issues which touch on questions of epistemology. Questions such as whether or not an increasing stock of knowledge makes it more or less difficult to acquire new knowledge may be better served by a philosophical framework, rather than a purely economic one. Another such question would be one of an optimum for access to existing knowledge. Theoretically, if the portion of knowledge available to the individual researcher, A_j were to reach parity with the total stock of knowledge, such that $A_j = A$, would that entail a flattening of the research productivity as the limits of a researcher's creativity imposed themselves? These questions, and others may not be suited for an economic analysis but rather a philosophical one. The answers however, would have important implications for the theory of economic growth.

The epistemological questions raised by the notion of a cumulative stock of knowledge and a research sector devoted to the production novel designs may have answers with important ramifications. Whether or not new ideas progressively become more difficult to produce is a question of huge importance to theories of long run economic growth.

6.4 Final Remarks

This paper has been an inquiry into three variables which are potential determinants of the productivity parameter (δ) in Paul Romer’s (1990) model of endogenous technological change and economic growth. The factors at play in determining a society's ability to produce new knowledge, producing more from less and thereby expanding the scope of human welfare are surely worthy of careful study. Hopefully these pages raise questions, the answers to which may in some sense increase our understanding of a phenomenon so central to our way of life.

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