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Path Dependence and Induced Innovation

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Abstract

This paper presents an endogenous growth model that captures the origins of path dependence and technological lock-in and introduces a mechanism of induced innovation, which can trigger new research. Imperfect spillovers of secondary development can make the development of new technologies unattractive until research ceases in the long run. Changes in the relative supply of primary factors act as a stimulus for research as new technologies are better suited for the new environment. A simulation using changes of crude oil prices in the US shows the quantitative significance of the model's implications. The model is able to explain long waves of economic development where growth cycles are triggered by changes in the relative factor supply. It also provides a new rationale for governmental regulations such as Pigouvian taxes and pollution permits as they can stimulate innovation and provide the base for the development of "green" technologies.

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1 Introduction

In this paper, I develop a model of path dependence, where the establishment of a dominant technology leads to a technological lock-in, and propose a mechanism of induced innovation, by which changes in the relative factor supply stimulate new research and allow to replace the dominant technology.

Path dependence denotes the fact that the trajectory of technological development depends on previous decisions and outcomes. The worldwide dominance of the light-water nuclear reactor despite the fact that it is considered inferior to other reactor types, is an example for this phenomenon. The success of the light-water reactor originates from the strong research founded by the US navy, who needed a small reactor as energy source for its submarines. This gave this reactor type a headstart over competing designs, so that it also became the dominant technology for stationary nuclear power plants (Cowan, 1990). Another prominent example is the QWERTY keyboard, which became an industry standard upon introduction with the first typewriters and could not be replaced by better keyboard layouts because typists had been trained for it already (David, 1985).

Path dependence can result from a number of origins. In his seminal article, Arthur (1989) points out the existence of specific human capital, that cannot be used for the competing technologies, network effects and technical interrelatedness, as well as increasing returns that hinder new technologies from overcoming the existing technology. Farrell and Saloner (1985, 1986) add the existence of standards and a large installed base as factors supporting the establishment of a dominant technology. Also headstart advantages and setup costs may prohibit the development of new technologies that may have a higher potential but are less productive in the short run.

Nevertheless, such a technological lock-in does not have to persist forever. Changes in the environment may provide enough incentives to overcome the dominant technology and to develop alternatives. This notion has been proposed already by Hicks (1932), who postulated that

"A change in relative prices of factors of production is itself a spur to invention, and to invention of a particular kind - directed towards economizing the use of a factor which has become relatively expensive."

The second part of this statement has found enormous attention by the literature on directed technical change during the last years, for example in Acemoglu (1998, 2002, 2007), Kiley (1999), and Jones (2005).[1] Although this paper is related to that literature, the focus here lies on the first part of Hicks' statement. Can changes in the relative supply of factors provide an incentive to research and lead to new innovations that replace the predominant technology?

A real world example for this idea is the automobile industry. During the course of the twentieth century, the development of electrical cars has ceased and gasoline cars have become the

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[1] While Hicks focused on the effect of price changes, the modern literature on directed technical change typically assumes exogenous changes in the (inelastic) relative supply of factors with relative prices being determined endogenously in equilibrium. This paper follows this line as this allows to compare the results with the current literature. The common denominator with Hicks' statement lies in the idea that a certain factor becomes relatively abundant or scarce.

only widespread technology. However, in recent years the development of electrical, hydrogen or hybrid vehicles has gained new momentum. With fossil fuels becoming scarce and expensive in the near future and ongoing climate change debates, alternatives to gasoline have become attractive again. At the end of the 1990s, the world's biggest car manufacturer Toyota introduced the Prius, a hybrid car that combines gasoline and electrical engines, which became a huge success. Now in 2015, all major car manufacturers work on concepts for alternative drive systems or have already brought the first models to the market. So, the prospective change of the availability of natural resources has triggered new research, which will lead eventually to the replacement of gasoline cars.

The model developed in this paper captures both the origins of path dependence that lead to technological lock-in as well as the induced innovation, that can lift the economy out of the trap again. The endogenous growth model is based on two sources of productivity growth: fundamental research and secondary development that builds on fundamental innovations. Secondary development is linked to a particular fundamental technology and cannot be transferred to the next fundamental innovation. With this, the expected productivity gain of a new fundamental innovation decreases as the stock of secondary knowledge for the current fundamental technology grows. This makes fundamental research less attractive and thus lowers the probability for a new innovation. In the long run, this leads to a technological lock-in and fundamental research ceases.

However, fundamental research does not only improve the productivity in general but can also be directed to increase the relative marginal productivity of a particular input factor. With this, fundamental researchers can react to changes in the relative factor supply and tailor a new innovation optimally for the new resource endowment. Hence, if the relative factor supply in the economy changes over time, the new fundamental innovation gains an advantage over the predominant technology, which makes fundamental research attractive again, so that the technological lock-in can be overcome.

With this result, the model is able to explain long wave patterns of economic development, where periods of strong growth alternate with slow growth phases. Changes in the relative supply of production factors induce new fundamental innovations, leading to a high-growth phase, which slowly fades out until the next fundamental innovation is triggered by a change in the resource endowment. The model can also explain technological backlashes, where factor price changes can lead to the development of new technologies, which are replaced again by the previous technology shortly after, when the price regime switches back to the old level. Examples for this pattern can be found during the energy crises of the 1970s when research into alternative energy sources and engines soared but was quickly dropped again during the oil glut of the 1980s.

To illustrate the quantitative significance of the model's implications, I simulate the effect of the relative changes in the crude oil price compared to renewable energy sources in the US from 1870 onward. The simulation results indicate that fundamental research and hence productivity growth is triggered by changes in the oil price. Due to the ongoing price changes, fundamental research is stimulated again and again and does not die out over time. By contrast, in the cross-check simulation without price changes, fundamental research and productivity growth cease over time and the economy becomes trapped in a technological lock-in. This indicates that the model's implications are quantitatively relevant.

This paper adds to the literature on path dependence and technological lock-in, where agents decide on adopting new technologies, while specific human capital or secondary development may stop them from doing so (Arthur, 1989; Brezis et al., 1993; Chari and Hopenhayn, 1991; Parente, 1994; Jovanovic and Nyarko, 1996). This paper is most closely related to Redding (2002), who proposes a model of endogenous growth, in which path dependence can lead to a technological lock-in. This model continues that work and adds a mechanism by which induced innovation can lift the economy out of the lock-in. This allows for growth and fundamental research in the long run, whereas in Redding's model, there was no possibility to continue research.

The paper is linked to the literature on directed or biased technological progress which has its origin in the ideas of Hicks (1932) and was formally characterized initially in the works of Fellner (1961), Kennedy (1964), Samuelson (1965), Ahmad (1966), Drandakis and Phelps (1966), and Binswanger (1974).[2] Since the seminal article by Acemoglu (2002), who proposed a micro-founded endogenous growth model in which changes in the supply of primary factors lead to directed technological change, this literature has attained new momentum (Acemoglu, 1998, 2007; Kiley, 1999; Jones, 2005; Wing, 2006). Recent empirical studies have found supportive evidence for directed technological progress. Newell et al. (1999) show that the energy price hikes due to the oil crises induced the development of more energy-efficient air-conditioners; Popp (2002) finds that higher energy prices have significantly increased the relative amount of energy-saving innovations in the U.S.; a similar result is obtained by Lanzi and Sue Wing (2011) for a panel of OECD countries; and Aghion et al. (2012) demonstrate that increased fuel prices raised the number of clean innovations in the U.S. automobile industry.

In this paper, the focus is not so much on the mechanism that determines the direction of technological change but more on the innovation stimulus that is triggered by a change in the relative supply of primary factors. Nevertheless, the model's implications concerning the bias of technological progress for relative factor supply changes are in line with the literature. With the focus on induced innovation, this paper also contributes to the growing literature on environmental protection and technological change (Goulder and Schneider, 1999; Unruh, 2002; Acemoglu et al., 2012a,b; Gans, 2012). In difference to those models, here, changes in the relative supply of primary factors, which may come in the form of Pigouvian taxes on fossil fuels or pollution permits, can induce a "green" innovation which displaces the dominant "dirty" technology and thus increase the total innovation rate.

Finally, this paper adds to the literature on long-run patterns of economic development and growth cycles (Kondratieff, 1984; Schumpeter, 1939; Mensch, 1979; Marchetti and Nakicenovic, 1979; Graham and Senge, 1980; Volland, 1987; Grübler and Nakicenovic, 1991). The model proposes an analytical explanation based on the decisions of rational agents how new cycles are

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[2] See also Acemoglu (2003) for an overview of the early literature.

triggered by changes in the supply of production factors, which is a stylized fact in long wave analysis.

The paper is organized as follows: the next section introduces the model; Section 3 derives the economy's equilibrium and the paper's main results; Section 4 analyzes the bias of technological change that is induced by a change in factor supply and compares it to the results of the existing literature; in Section 5, the effect of oil-price changes for the US economy is simulated; and Section 6 concludes and discusses opportunities for future research.

2 The Model

General Setup

The model is set in discrete time on an infinite horizon. The economy is populated with overlapping generations of uniform agents of mass one who live for two periods. Each agent is endowed with one unit of labor per period. In addition, there is an exogenously given perfectly inelastic supply of primary inputs Q and Z in every period. These primary inputs are supplied competitively at market prices p^Q, p^Z and are not owned by the agents.[3] Generations are indexed by $t \in [1, \infty)$ and lifetime periods by 1 and 2 such that p^Q_{2t} refers to the price of input Q in the second life period of generation t for example.

The economy comprises four sectors: Fundamental research and secondary development, which take place during the first period of an agent's life, and intermediate and final goods production during period 2. Each final good producer produces an individual final good indexed by i. These final goods are imperfect substitutes for consumption. Intermediate goods are produced from primary inputs Q, Z and used for final goods production. Each fundamental innovation creates a new type of intermediate good. The different types of intermediate goods that are available are indexed by k.

Fundamental research is modeled as directed technological progress with uncertain success that generates a sequence of blueprints for intermediate goods production technologies with increasing productivity. Secondary development takes place under certainty and takes the form of continuous productivity improvements in final goods production. Secondary development is specific to a particular type of intermediate good, similar to Brezis et al. (1993), Jovanovic and Nyarko (1996), and Redding (2002). This implies that for each new fundamental innovation, which produces a new type of intermediate good, the stock of secondary knowledge has to be accumulated again.

The total productivity of the economy in terms of transforming raw inputs into final goods is determined by the joint productivity of intermediate and final goods production and depends on the type of intermediate good that is used and the stock of secondary knowledge that has been developed for this type of intermediate good. This is illustrated in Figure 1.

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[3] These assumptions are not necessary for the results but simplify the analysis of the equilibrium.

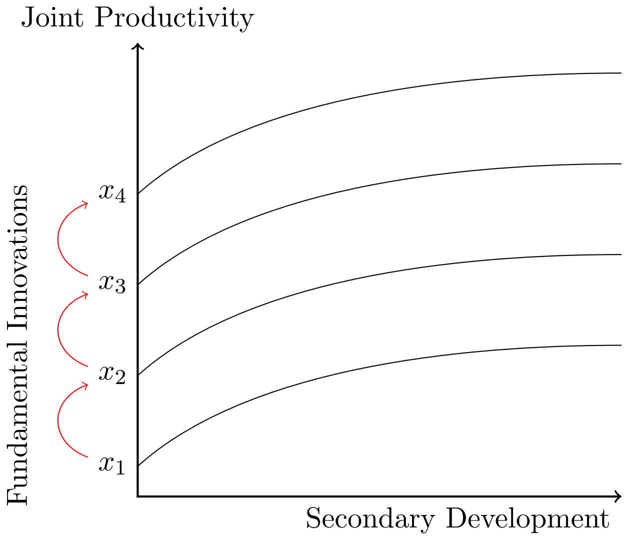

Figure 1: Joint productivity of fundamental technology and secondary development

Timing of Decisions

At the beginning of period 1, newborn agents inherit the blueprints for intermediate goods production technologies from previous generations and the body of secondary knowledge that has been accumulated up to this time.[4] The agents then decide whether to become fundamental researchers or secondary developers. In the remainder of period 1, fundamental researchers aim to discover a new technology for intermediate goods production while secondary developers augment the body of secondary knowledge for a chosen type of existing intermediate good. During this process, the latter also acquire the skills needed to become final good producers in period 2. Consequently, the initial decision to continue along fundamental research or secondary development marks a decision on lifetime labor supply.

At the end of period 1, all research uncertainty is revealed. If a success in fundamental research has been made, the successful researcher becomes the monopoly supplier of the new type of intermediate good in period 2. If no new fundamental innovation has been made, an already existing type of intermediate good is produced competitively. Secondary developers become final good producers under monopolistic competition; unsuccessful fundamental researchers have no profession in the second period.

Production and Consumption

Intermediate goods production uses primary inputs Q and Z in a CES production function with constant returns to scale,

$$x_{2t,k} = A_k \left[\psi_k^{\frac{1}{\epsilon}} Q_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_k)^{\frac{1}{\epsilon}} Z_{2t}^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}} . \tag{1}$$

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[4] The inherited technologies and secondary development constitute the endogenous state variables of the economy.

The productivity of intermediate goods production A_k and the share parameter ψ_k are linked to the type of intermediate good x_k. They are determined in the process of fundamental research which is specified below. The market price of intermediate goods is denoted p^x_k.

Final good producers use a linear CRS production function and the intermediate good as input,

$$y_{2t,i} = S_{2t,k}\, x_{2t,k}(i), \tag{2}$$

where $S_{2t,k}$ denotes the stock of secondary knowledge for intermediate good x_k that has been accumulated. It is implicitly assumed, that all final goods producers possess the same amount of secondary knowledge. Given that the agents inherit the body of secondary knowledge at the beginning of period 1, this assumption states that all secondary developers are equally productive in augmenting the stock of secondary knowledge. This assumption can be relaxed to give $y_{2t,i} = S_{2t,k}(i)x_{2t,k}(i)$, however, this does not change the results and only complicates the model.

All production activities take place in period 2, hence income is only generated in the second life period of each generation. There are no credit markets, so consumption takes place only in period 2. Agents are indexed by j; they are risk neutral and do not suffer disutility from supplying labor. They have Dixit-Stieglitz type preferences on the basket of final goods, so the lifetime utility of an individual agent is given by

$$u_{t,j} = \left(\int_0^{L_t} c_{2t,i}(j)^{\rho}\, \mathrm{d}i \right)^{\frac{1}{\rho}}, \tag{3}$$

where $c_{2t,i}(j)$ denotes the agent's consumption of final good $y_{2t,i}$ at price $p^y_{2t,i}$ and L_t denotes the measure of final good producers in generation t, which gives the range of different final goods.[5] Since final goods are imperfect substitutes, $0 < \rho < 1$.

Fundamental Research

Fundamental researchers try to discover a better production technology for intermediate goods. Let x_m denote the latest type of intermediate good that is available at the start of the first period of generation t. Every researcher creates an innovation that results in a new type of intermediate good x_{m+1} with probability p. The successful innovator obtains a patent for the innovation that is valid for one period (that is until the end of the innovator's life). Let R_t be the mass of researchers of generation t. Since R_t consists of infinitely many elements, the resulting aggregate innovation probability is approximated by a Poisson distribution (Feller, 1950). Hence the aggregate probability that a new innovation is made is given by

$$\Omega(R_t) = 1 - \mathrm{e}^{-pR_t}. \tag{4}$$

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[5] L_t does not carry an index for the lifetime period since the decision for labor supply is a lifetime decision and L_t refers to the mass of secondary developers in generation t in the first lifetime period and to final good producers in the second period.

If more than one innovation is created, the patent is attributed to one of the innovators by lottery. The individual probability of obtaining the patent for a new technology is given by

$$P(R_t) = \frac{1 - \mathrm{e}^{-pR_t}}{R_t}. \tag{5}$$

The aggregate probability to discover a new fundamental technology increases in R_t whereas the individual probability to obtain a patent decreases in R_t.

Fundamental research can be directed so that not only general productivity is increased but also the relative marginal product of one particular input factor. This means that researchers can adjust the intermediate goods production technology if the relative supply of primary factors Q, Z changes, in order to use these resources optimally.

The effect of a new fundamental innovation is composed of two parts. First, the general productivity of intermediate goods production evolves with productivity factor A according to

$$A_{m+1} = \gamma A_m = \gamma^{m+1} A_0 \quad \text{with } \gamma > 1, \tag{6}$$

where A_0 is normalized to 1. Second, fundamental innovators adjust the direction of technological progress by choosing the optimal share parameter ψ_{m+1} for the intermediate goods production function, which changes the relative marginal productivity of the input factors.

Secondary Development

The stock of secondary knowledge for a specific intermediate good is increased by secondary developers during the first lifetime period of every generation. Secondary development is regarded as a product of the following three processes: the accumulation of specific human capital needed to use the respective fundamental technology efficiently, engineering refinements that make the fundamental technology more productive, and the creation of supplementary technologies and networks that are needed to release the productive potential of the underlying fundamental technology. These achievements are specific for every underlying fundamental technology. So when a new fundamental technology is discovered, secondary development starts from the beginning again. These assumptions capture the essence of the origins of path dependence as described in the introduction.[6]

Secondary development features diminishing marginal returns so that the marginal productivity improvements decline with ongoing secondary development. When a new technology in form of a fundamental innovation is introduced, final good producers have to accommodate themselves with this technology and learn to use it efficiently. At the beginning, this will lead to great productivity improvements but further gains in efficiency are harder to achieve. Also a new technology is most often not perfect at the start-up but rather comes as a beta-version. So in the early days, there are a lot of possibilities for improvements (Rosenberg, 1994). After the

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[6] The assumption of zero spillovers of secondary development can be relaxed to allow for imperfect spillovers between fundamental technologies, so that a part of the accumulated stock of secondary development can be used with a new fundamental technology, similar to Redding (2002). This does not change the fundamental results of the model.

first important rework has been undertaken, future improvements will be of lesser importance until finally the productive potential of the underlying technology is completely released.[7]

Secondary developers decide for which type of intermediate good they undertake secondary development and spend the first period augmenting the stock of secondary knowledge for this technology. The stock of secondary knowledge for the chosen technology x_k evolves during the agents' first lifetime period according to

$$S_{2t,k} = \mu S_{1t,k}^{\phi} \quad \text{with: } \mu > 1,\ 0 < \phi < 1, \tag{7}$$

where $S_{1t,k}$ denotes the stock of secondary development for technology k that has been inherited from the previous generation.

Notice, that due to diminishing returns of secondary development, the economy can exhibit growth in the long run only by fundamental innovations. This is similar to the assumptions in Jovanovic and Nyarko (1996).

3 Equilibrium

Given the time structure of decisions, the model is solved by backward induction for the decisions of an arbitrary generation t and given number of fundamental technologies available with corresponding body of secondary development. First, I derive the equilibrium in final and intermediate goods markets in period 2 for a given number of fundamental researchers and secondary developers. Two states of the world have to be considered in this analysis: successful and unsuccessful fundamental research in period 1. After that, the equilibrium allocation of fundamental research and secondary development in period 1 as well as the choice of a fundamental technology for secondary development and the direction of fundamental research is obtained.

Period 2

The equilibrium in the final goods market is independent of success in fundamental research in period 1. Agents optimize their consumption portfolio subject to their preferences given in (3) and their individual budget constraint

$$\int_0^{L_t} p_{2t,i}^{y}\ c_{2t,i}(j)\ \mathrm{d}i \leq E_{2t}(j), \tag{8}$$

where $E_{2t}(j)$ denotes the agent's income in period 2, depending on his lifetime labor decision and research success.

This yields individual demand for each type of final good

$$c_{2t,i}(j) = \left(\frac{p_{2t,i}^{y}}{P_{2t}}\right)^{-\frac{1}{1-\rho}} \frac{E_{2t}(j)}{P_{2t}}, \tag{9}$$

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[7] See also the discussion in Doraszelski (2004) about different specifications for secondary development.

with price index

$$P_{2t} = \left[\int_0^{L_t} {p^y_{2t,i}}^{-\frac{\rho}{1-\rho}} \, \mathrm{d}i \right]^{-\frac{1-\rho}{\rho}} . \tag{10}$$

Final goods producers maximize their profit, subject to demand for final goods derived above.

As in Dixit and Stiglitz (1977), the optimal competitive-monopoly price is a constant mark-up over marginal cost $MC^y_{2t,i}$

$$p^y_{2t,i} = \frac{1}{\rho} MC^y_{2t,i}.\text{[8]} \tag{11}$$

To derive the equilibrium results for intermediate goods production, the two possible cases for the period 1 outcome, successful and unsuccessful fundamental research, are considered separately.

Unsuccessful Fundamental Research in Period 1

If no fundamental innovation was made in period 1, all types of existing intermediate goods are free of patent protection and can be produced by competitive enterprises. Intermediate goods producers choose the type of intermediate good that delivers the highest joint productivity in combination with the body of secondary knowledge in period 2 to maximize their output. This involves a potential trade-off between productivity in intermediate goods production and productivity in final goods production, which depends on the stock of secondary knowledge that has been accumulated for each type of intermediate good. Let x_n denote the chosen intermediate good. The type n is defined by

$$S_{2t,n} A_n \left[\psi_n^{\frac{1}{\epsilon}} \bar{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_n)^{\frac{1}{\epsilon}} \bar{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}} = \sup_{k \leq m} \left\{ S_{2t,k} A_k \left[\psi_k^{\frac{1}{\epsilon}} \bar{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_k)^{\frac{1}{\epsilon}} \bar{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}} \right\}, \tag{12}$$

where $\bar{Q}_{2t},\ \bar{Z}_{2t}$ denote the exogenous supply of factors $Q,\ Z$ during this period.

Since intermediate goods production is competitive, the price $p^x_{2t,n}$ equals marginal production costs and intermediate goods producers make zero profits. Intermediate good x_n is the only type of intermediate good that is produced and it is taken as the economy's numeraire, so

$$p^x_{2t,n} = 1. \tag{13}$$

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[8] Since preferences are homothetic, the distribution of income among agents does not influence equilibrium mark-ups of final good producers (Foellmi and Zweimueller, 2003).

Since this type of intermediate good is used by all final good producers, marginal costs are the same for all types of final goods, hence

$$p^{y}_{2t,i} = p^{y}_{2t} = \frac{1}{\rho S_{2t,n}}. \tag{14}$$

Total demand for Q_t and Z_t equals the supply $\bar{Q}_t$, $\bar{Z}_t$, hence total intermediate goods production is given by

$$X_{2t,n} = A_n \left[\psi_n^{\frac{1}{\epsilon}} \bar{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_n)^{\frac{1}{\epsilon}} \bar{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}}. \tag{15}$$

Primary factors are paid their marginal value product

$$p^{Q}_{2t} = \frac{\partial A_n \left[\psi_n^{\frac{1}{\epsilon}} \bar{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_n)^{\frac{1}{\epsilon}} \bar{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}}}{\partial \bar{Q}_{2t}}, \quad p^{Z}_{2t} = \frac{\partial A_n \left[\psi_n^{\frac{1}{\epsilon}} \bar{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_n)^{\frac{1}{\epsilon}} \bar{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}}}{\partial \bar{Z}_{2t}}, \tag{16}$$

and the individual profit of final good producers is given by

$$\pi^{y}_{2t,n} = \frac{1-\rho}{\rho} \frac{X_{2t,n}}{L_t} \tag{17}$$

Successful Fundamental Research in Period 1

If fundamental research was successful in period 1, the innovator obtains a patent for the new intermediate good x_{m+1} and becomes the monopoly supplier of this intermediate good in period 2. The monopolist maximizes his profit given the demand for intermediate goods and takes the prices for primary inputs Q and Z as given[9]

$$\begin{aligned} &\max_{p^{x}_{2t,m+1}} \{ p^{x}_{2t,m+1} x_{2t,m+1} - p^{Z}_{2t} Z_{2t} - p^{Q}_{2t} Q_{2t} \}, \\ &\text{s.t. } x_{2t,m+1} = A_{m+1} \left[\psi_{m+1}^{\frac{1}{\epsilon}} Q_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_{m+1})^{\frac{1}{\epsilon}} Z_{2t}^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}}, \\ &\frac{p^{x}_{2tm+1}}{S_{2t,m+1}} \leq \frac{1}{S_{2t,n}}, \\ &S_{2t,m+1} = 1. \end{aligned} \tag{18}$$

Notice, that no secondary development has been undertaken yet for the new technology, therefore $S_{2t,m+1} = 1$. The resulting monopoly price is given by

$$p^{x}_{2t,m+1} = \frac{1}{S_{2t,n}}. \tag{19}$$

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[9] Even though the monopolist is the only buyer of primary factors in equilibrium, he is in competition with independent producers of intermediate goods of the next best quality n. Therefore he can not act as a monopsonistic buyer and takes factor prices as given.

This price secures the monopolist the whole market for intermediate goods because the marginal cost for final good producers are equal to the best available alternative x_n. Increasing the price would lead to zero profits because final good producers are not willing to pay a higher price and independent intermediate goods producers, who offer intermediate goods of type x_n would fill the gap. The price for the new intermediate good is lower than for intermediate goods of previous generations. The new intermediate good is equally productive as its predecessors but final goods producers have not had the time yet to build up secondary knowledge for the new type of intermediate good. Therefore, the new intermediate good is less attractive to them and only marketable at a lower price. However, the production of the new intermediate good needs less resources, so the monopolist is able to make a profit.

Since the marginal cost for final good producers is equal to that in the case of unsuccessful research in period 1, the price for a final good p^y_{2t} remains the same and is independent of research success.

Equilibrium intermediate goods output is given by

$$X_{2t,m+1} = A_{m+1}\left[\psi_{m+1}^{\frac{1}{\epsilon}}\bar{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_{m+1})^{\frac{1}{\epsilon}}\bar{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}, \tag{20}$$

and the profit for the successful fundamental researcher is given by

$$\pi^X_{2t,m+1} = \frac{1}{S_{2t,n}}\, X_{2t,m+1} - p^Z_{2t}\bar{Z}_{2t} - p^Q_{2t}\bar{Q}_{2t}. \tag{21}$$

Using the fact that $p^Z_{2t}\bar{Z}_{2t} + p^Q_{2t}\bar{Q}_{2t} = X_{2t,n}$, the monopolist's profit can be written as

$$\pi^X_{2t,m+1} = \frac{X_{2t,m+1} - S_{2t,n}X_{2t,n}}{S_{2t,n}}. \tag{22}$$

This equation makes it clear that the overall productivity based on the new type of intermediate good, even without any secondary development in the final goods sector, must be higher than the combined productivity of the competing intermediate goods production technology together with the respective stock of secondary knowledge. Otherwise fundamental researchers would not make positive profits, which implies that nobody would have wanted to become a fundamental researcher in the first period.

The final good producers' individual profit is given by

$$\pi^Y_{2t,m+1} = \frac{1-\rho}{\rho}\frac{X_{2t,m+1}}{S_{2t,n}L_t}. \tag{23}$$

Period 1

At the beginning of period 1, agents decide whether to become a fundamental researcher or to go into secondary development and become a final good producer in the second period. Fundamental researchers then have to decide, in which direction to focus their research, while secondary developers have to choose the type of existing intermediate good for which the stock of secondary knowledge will be increased. These decisions depend on the agents' expectations in the first period about the endowment with primary input factors in period 2. The expected supply of primary factors is denoted by $\tilde{Q}_{2t} \equiv \mathbb{E}_{1t}\left(\bar{Q}_{2t}\right)$ and similar for $\tilde{Z}_{2t}$.

The optimal choice for the type of intermediate good for secondary development is very similar to the choice of the best production technology in period 2. Secondary developers choose the intermediate good, for which the final goods output in the next period is maximized, given the expected factor supply in period 2 and the contribution to the secondary stock of knowledge by the developers themselves during the first period. The chosen technology $\tilde{n}$ is defined by

$$\mu S^{\phi}_{1t,\tilde{n}} A_{\tilde{n}} \left[\psi_{\tilde{n}}^{\frac{1}{\epsilon}} \tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_{\tilde{n}})^{\frac{1}{\epsilon}} \tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}} = \sup_{k \le m} \left\{ \mu S^{\phi}_{1t,k} A_k \left[\psi_k^{\frac{1}{\epsilon}} \tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_k)^{\frac{1}{\epsilon}} \tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}} \right\}. \tag{24}$$

If the relative supply of input factors is expected to remain constant, the chosen technology for secondary development $\tilde{n}$ is the same technology that is currently used by the previous generation for production in their second lifetime period. Furthermore, if the relative factor supply actually remains constant, than technology $\tilde{n}$ is identical to technology n, which is chosen for production in period 2.[10]

Fundamental researchers decide on the optimal share parameter ψ_{m+1} that determines the relative productivity of the primary factors Q, Z with the new intermediate goods production technology, taking the expected supply of these factors in the next period into account. Equation (22) shows that the prospective monopolist's profit increases in the amount of intermediate goods that can be produced with the given amount of $\bar{Q}_{2t}$ and $\bar{Z}_{2t}$. Therefore, fundamental researchers choose $\psi^*_{m+1}(\tilde{Q}_{2t}, \tilde{Z}_{2t})$ to maximize expected output from intermediate goods production:

$$\psi^*_{m+1}(\tilde{Q}_{2t}, \tilde{Z}_{2t}) = \arg\max\ \gamma A_m \left[\psi_{m+1}^{\frac{1}{\epsilon}} \tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_{m+1})^{\frac{1}{\epsilon}} \tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}. \tag{25}$$

Proposition 1. *For $\epsilon \neq 1$, a unique interior solution for the optimal value of ψ_{m+1} exists, that maximizes intermediate goods production subject to the economy's expected relative factor supply. The optimal ψ_{m+1} is unique for every expected relative supply of primary factors $\frac{\tilde{Z}_{2t}}{\tilde{Q}_{2t}}$.*

Proof. For the proof, derive the first order condition for maximization of equation (25). This gives

$$\psi_{m+1} = \frac{\tilde{Q}_{2t}}{\tilde{Q}_{2t} + \tilde{Z}_{2t}},$$

which proves both parts of the proposition. □

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[10] This could of course also be true if the actual relative factor supply in the second period is different but technology $\tilde{n}$ is still the best available technology. However, this is not necessarily the case.

Corollary 1. *If the expected relative supply of primary input factors remains constant after a fundamental innovation, fundamental researchers of the following generations do not change the share parameter* ψ *in their research.*

Corollary 1 states that once the intermediate goods production technology has adjusted to a certain relative supply of input factors, technological progress becomes factor neutral. Only if the relative supply of input factors changes (or is expected to change), fundamental research becomes biased and changes the relative marginal productivity of input factors.

The final step to close the model is to determine the equilibrium levels of employment in fundamental research and secondary development. An individual fundamental researcher makes an innovation and receives a patent with probability $P(R_t)$. This allows him to extract profits as the monopolistic intermediate goods producer in the second period. An unsuccessful researcher gains zero profits. The expected lifetime income of a fundamental researcher is thus given by

$$V_t^R = \\ P(R_t)\,\frac{\gamma^{m+1}\left[\psi_{m+1}^{\frac{1}{\epsilon}}\tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}}+(1-\psi_{m+1})^{\frac{1}{\epsilon}}\tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}-\mu S_{1t,\tilde{n}}^{\phi}\gamma^{\tilde{n}}\left[\psi_{\tilde{n}}^{\frac{1}{\epsilon}}\tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}}+(1-\psi_{\tilde{n}})^{\frac{1}{\epsilon}}\tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}}{\mu S_{1t,\tilde{n}}^{\phi}}. \tag{26}$$

Final goods producers are able to extract competitive-monopoly profits irrespective of success in fundamental research in period 1. However, successful fundamental research increases the profits of final goods producers. So the expected lifetime profit for secondary developers is given by

$$V_t^S = \Omega\left(R_t\right)\frac{1-\rho}{\rho}\frac{\gamma^{m+1}\left[\psi_{m+1}^{\frac{1}{\epsilon}}\tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}}+(1-\psi_{m+1})^{\frac{1}{\epsilon}}\tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}}{\mu S_{1t,\tilde{n}}^{\phi}\left(1-R_t\right)} \\ +\big(1-\Omega\left(R_t\right)\big)\frac{1-\rho}{\rho}\frac{\gamma^{\tilde{n}}\left[\psi_{\tilde{n}}^{\frac{1}{\epsilon}}\tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}}+(1-\psi_{\tilde{n}})^{\frac{1}{\epsilon}}\tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}}{1-R_t}, \tag{27}$$

where the fact is used that $L_t = 1 - R_t$. It can be seen that if the mass of fundamental researchers nears one, the profit of secondary developers becomes infinite, hence there will be always a positive amount of secondary developers in equilibrium. With this, the arbitrage equation that determines the amount of fundamental and secondary researchers is given by

$$V_t^R \leq V_t^S, \tag{28}$$

which can be rearranged to yield

$$1 \geq \frac{\gamma^{m+1-\tilde{n}}}{\mu S_{1t,\tilde{n}}^{\phi}} \left[\frac{\psi_{m+1}^{\frac{1}{\epsilon}} \tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_{m+1})^{\frac{1}{\epsilon}} \tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}}{\psi_{\tilde{n}}^{\frac{1}{\epsilon}} \tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_{\tilde{n}})^{\frac{1}{\epsilon}} \tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}} \right]^{\frac{\epsilon}{\epsilon-1}} \frac{\rho - (1-\rho)\frac{R_t}{1-R_t}}{\rho + (1-\rho)\frac{1-\Omega(R_t)}{\Omega(R_t)}\frac{R_t}{1-R_t}}. \tag{29}$$

Proposition 2. *If the arbitrage equation is binding, a unique positive equilibrium level of fundamental researchers R_t exists.*

Proof. The nominator of the RHS of (29) strictly decreases in R_t, whereas the denominator increases in R_t. While the first part can be directly seen, showing the monotonous behavior of the denominator demands more work. The derivative of the nominator with respect to R_t is given by

$$\frac{\partial \left(\rho + (1-\rho)\frac{e^{-pR_t}}{1-e^{-pR_t}}\frac{R_t}{1-R_t} \right)}{\partial R_t} = (1-\rho)\frac{e^{-pR_t}\left(1-e^{-pR_t} - pR_t(1-R_t)\right)}{\left(1-e^{-pR_t}\right)^2 (1-R_t)^2}. \tag{30}$$

Equation (30) is non-negative iff:

$$1 - e^{-pR_t} - pR_t(1-R_t) \geq 0. \tag{31}$$

The left side of above expression is strictly convex and the global minimum of the function is at $R_t = 0$. Plugging this result back into (31) validates the fact that the nominator of the arbitrage equation increases in R_t. Hence the RHS of the arbitrage equation is strictly decreasing in the number of fundamental researchers, whereas the LHS is constant, so a unique equilibrium exists if the arbitrage condition is fulfilled. □

If the arbitrage equation is not binding, the expected lifetime income of fundamental research is always lower than that of secondary development and there is no fundamental research in equilibrium.

Proposition 3. *Equilibrium employment in fundamental research is monotonically decreasing in the stock of accumulated secondary knowledge $S_{1t,\tilde{n}}$ for the best existing type of intermediate good $x_{\tilde{n}}$. Further, a critical value for the stock of accumulated secondary knowledge $S_{1t,\tilde{n}}^{*} > 1$ exists at which equilibrium employment in fundamental research becomes zero and technological lock-in occurs.*

Proof. The RHS of the arbitrage equation is decreasing in $S_{1t,\tilde{n}}$ and decreasing in R_t, so the number of fundamental researchers decreases as $S_{1t,\tilde{n}}$ increases. The second part follows directly. □

Proposition 2 captures the essence of the problem of path dependence. The more secondary investment has been put into an existing technology, the more difficult it becomes for a new technology to outperform its predecessor. This makes searching for new technologies less attractive, since the profit that can be earned decreases. The negative effect of the existing stock of secondary development on the equilibrium level of fundamental research is depicted in Figure 2.

In this model, two competing forces that determine the profitability of a fundamental innovation exist. On the one hand, each new type of intermediate good yields a productivity gain in intermediate goods production. On the other hand, there is a loss of productivity in final goods production, that comes from loosing the stock of secondary knowledge when production switches to the new type of intermediate good. As long as the first effect is stronger, a new type of intermediate good yields an overall improvement in productivity, from which profits for the successful fundamental innovator can be extracted. However, the larger the stock of secondary knowledge that benefits the existing rival intermediate good grows, the lower the productivity gain from using a new intermediate good becomes. Consequently, the potential monopoly profit for fundamental researchers decreases. Therefore, fewer agents are willing to undertake fundamental research while a greater number prefers to work as secondary developers. This process aggravates until no agent finds it attractive any more to engage in fundamental research.

This results in a technological lock-in in which no fundamental research is conducted and no new types of intermediate goods are produced. With the assumptions on the evolution of the productivity of intermediate goods production by fundamental research (6) and the improvements of final goods production by secondary development (7), it becomes clear that unlimited growth is only possible through fundamental innovations. Secondary development gradually releases the underlying productive potential of the associated intermediate good. Once this potential is completely exhausted, there is no further room for improvement. Therefore, the economy cannot grow endlessly through secondary improvements alone. Once the economy has been trapped in a technological lock-in, economic growth will quickly cease.

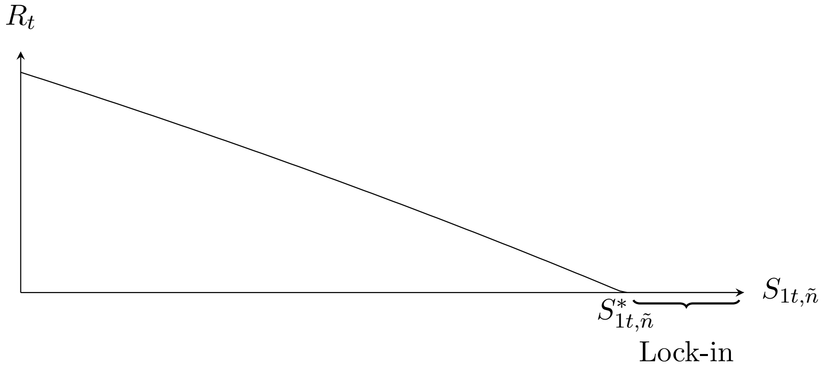

Figure 2: Equilibrium number of fundamental researchers with respect to accumulated secondary development

The process of becoming trapped in an equilibrium with no fundamental research is self-reinforcing. Every period without success in fundamental research, the stock of secondary knowledge for the competing intermediate good increases. This makes fundamental research less attractive for workers of the next generation, resulting in a smaller number of fundamental researchers. Consequently, the probability to make a new fundamental innovation in the next period is lowered. So with every period without fundamental research success, the probability to end up in a no-growth equilibrium increases. Fewer and fewer workers find it attractive to become fundamental researchers until fundamental research ceases completely.

Proposition 4. *Let $\epsilon \neq 1$, then a change in the expected relative supply of primary factors $\frac{\tilde{Q}_{2t}}{\tilde{Z}_{2t}}$ compared to the situation when the production technology for the competing type of intermediate good $x_{\tilde{n}}$ was developed, increases the equilibrium number of workers in fundamental research.*

Proof. By Proposition 1, for every expected relative supply with primary factors $\frac{\tilde{Q}_{2t}}{\tilde{Z}_{2t}}$, a unique optimal ψ^* exists. Therefore, if the expected relative resource endowment has changed since the competing type of intermediate good $x_{\tilde{n}}$ was developed, fundamental researchers will change the share parameter so that $\psi_{m+1} \neq \psi_{\tilde{n}}$. Furthermore, since ψ_{m+1} is chosen to be the optimal ψ^* for the expected relative endowment $\frac{\tilde{Q}_{2t}}{\tilde{Z}_{2t}}$, it is true that

$$\left[\frac{\psi_{m+1}^{\frac{1}{\epsilon}} \tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_{m+1})^{\frac{1}{\epsilon}} \tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}}{\psi_{\tilde{n}}^{\frac{1}{\epsilon}} \tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_{\tilde{n}})^{\frac{1}{\epsilon}} \tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}}\right]^{\frac{\epsilon}{\epsilon-1}} > 1.$$

This implies that the right hand side of the arbitrage equation (29) increases when the expected relative supply of primary factors in the economy changes. Since the right hand side of the arbitrage equation decreases in the number of fundamental researchers, a change in the relative endowment with primary factors results in a higher number of fundamental researchers. □

Corollary 2. *If the change in the expected relative supply of primary factors is large enough, fundamental research R_t is positive.*

Proposition 4 captures the original idea of induced innovation. Just as in Hicks (1932), it states that a change in the availability of factors of production stimulates innovation. The intuition behind Proposition 4 is as follows. A new fundamental innovation has to compete against previous types of intermediate goods which have already benefited from secondary development, however, it has the advantage that it can be adapted to a change in relative factor supply. Hence, if the relative supply of primary factors changes, the productivity gain of the new fundamental innovation becomes larger. The opportunity to adjust the direction of technological change makes the new fundamental innovation more profitable and thus provides an incentive for workers to go into fundamental research. This effect becomes stronger, the stronger the change in the relative factor supply is.

If the economy has been trapped in a technological lock-in, a change in the relative supply of primary factors can make fundamental research attractive again, which is captured by Corollary 2. With the possibility to adapt the new fundamental technology to the change in relative factor supply, the new innovation now outperforms the legacy technology which was created for a different resource regime. The probability to escape a lock-in increases, the stronger the change in the relative supply of primary factors is. Notice, that a great change in the relative endowment does not have to come within one period but the relative supply may change in little steps. As long as the incentive effect is not strong enough, fundamental research does not start.

However, once the difference between the actual relative factor supply and the endowment for which the competing technology had been developed has become large enough, fundamental research becomes attractive again and starts anew.

If the relative factor supply has enough variation over time, the model is able to generate technological progress and economic growth in the long run. During periods with little variation in the supply of primary factors, employment in fundamental research may go down until fundamental research stops and technological progress eventually ceases. However, if at some point in time substantial shifts in the relative factor supply occur, or if over time small changes accumulate to larger ones, the economy is lifted out of the lock-in and fundamental research starts again. The result is permanent growth that fluctuates between periods with more fundamental research and periods with little or no fundamental research.

The positive effect of a change in the relative supply of primary factors on fundamental research is illustrated in Figure 3. Similar to Figure 2, it shows the amount of fundamental research as a function of the stock of secondary development that has been accumulated for the competing technology. The solid line depicts the basic scenario with no changes in the relative factor supply where fundamental research ceases for a high level of secondary development. The dashed line in contrast displays the amount of fundamental research when the relative factor supply has changed by 25%.[11] It can be seen that the amount of fundamental research increases for all levels of secondary development. With this, secondary development has to be higher before fundamental research ceases. The dash-dotted line shows the results for a change in the relative factor supply by 50%. It turns out, that the increase in fundamental research is much higher now, so the positive effect of induced innovation grows progressively as the relative factor supply changes.

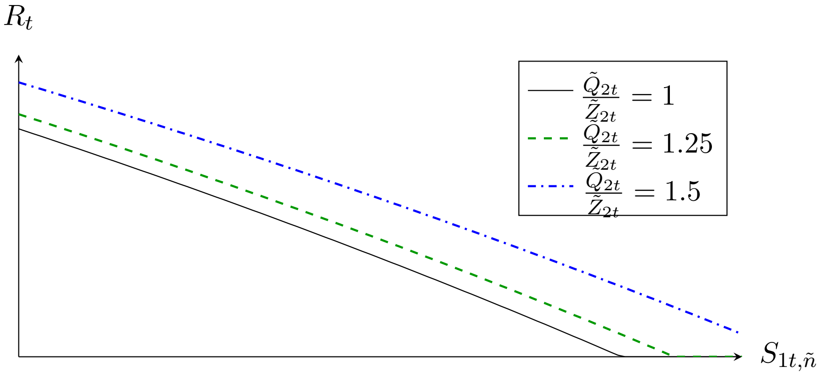

Figure 3: Effect of changes in relative factor supply on fundamental research

An important implication of the model is that governmental regulations, that affect the availability of primary factors, can act as a stimulus to innovative activity and induce new innovations. This becomes especially relevant in the context of environmental protection. A growing literature discusses the possibilities and limitations of bringing the economy on a clean growth track that avoids the growth of greenhouse gas emissions and the depletion of natural resources

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[11] The direction of the change does not play a role.

(Goulder and Schneider, 1999; Unruh, 2002; Acemoglu et al., 2012a,b; Gans, 2012). This model predicts, that regulations reducing the availability of the factor which is harmful to the environment, for example a limitation of pollution permits or Pigouvian taxes on fossil fuels, induce the development of technologies that use the now scarce factor less.

Unlike other models such as Acemoglu et al. (2012a,b), the process of switching to a new technology with a different input factor utilization does not take place gradually but rather comes as one fundamental new innovation like the change from gasoline cars to electrical vehicles or from fossil-fuel based electricity generation to solar energy. However, this implies also that the push from governmental regulation (or natural changes in the relative supply) must be strong enough to overcome the technological lock-in. Hence small regulations may have no effect as they are not sufficient to induce a replacement of the dominant technology. This could lead to the wrong conclusion that this kind of policy is not able to put the economy on a clean growth track, however, the truth is that the policy has to be intensified to increase the changes in the relative factor supply and induce the switch to a clean technology.

The model is also able to provide an explanation for the long wave patterns of economic development, also known as Kondratiev waves, during which periods with rapid growth are followed by periods with little or no growth. In this model, a new fundamental innovation produces drastic technological progress followed by a high-growth phase with strong secondary development, which yields the upswing phase of the cycle. Then in the downswing phase, secondary improvements slowly fade out until the next fundamental innovation arrives. Many authors point out that the turning points of these movements are marked by strong changes in the price of commodities; especially the scarcity or price peak of the current dominant energy source marks the begin of a new cycle (Graham and Senge, 1980; Marchetti and Nakicenovic, 1979; Volland, 1987; Grübler and Nakicenovic, 1991). In the model presented here, these price changes lead to increased fundamental research, which can trigger a new fundamental innovation and thus start a new growth cycle. So the model is able to replicate this stylized fact.

An example for the start of such a long economic cycle is the process in the eighteenth century leading to the Industrial Revolution in England. As Acemoglu (2002) points out, the great increase in skill-replacing technologies which took place in England at that time, coincided with the sudden increase in the supply of unskilled workers due to migration and other effects. Acemoglu concludes, that this increase was the source for the bias of technological progress towards unskilled workers at this time. This paper follows this conclusion,[12] but goes one step further by arguing that the sudden increase in the availability of unskilled labor was also the very source of the rapid technological progress itself. The shift in the supply of unskilled workers provided the necessary incentive to introduce new technologies of cheap mass production that made use of these unskilled workers, compared to the previously dominating artisan production that required specialized craftsmen.

An interesting feature of the model is, that it can explain technological backlashes where a new technology is developed but is given up after a short time and replaced again by the previous

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[12] See also the next section on the direction of technical progress in the model compared to the results in Acemoglu (2002, 2007).

technology. This happens if a change in the supply of input factors is only a temporary shock. During the shock, new technologies are developed which are designed for the changed factor supply. Once the supply returns to the old state, legacy technologies that were designed for that factor supply become suddenly more profitable again than the newer interim technology. The big shocks to worldwide oil supplies during the oil crises in the 1970s provide an example for this switch-back effect. During that time, research in alternative energies and on economizing energy increased tremendously. In 1973, Europe's greatest research center for solar energy was founded in Almeria in Spain. Around the same time, a number of solar power plants were built in California and other parts of the US. However, as the oil price returned to a normal level after 1980, research in this direction was quickly given up and the few research solar power stations remained the only ones. So the newly developed technologies remained unused for mass commercial energy production. That is true until the late 1990s, when increasing energy prices and the public debate about climate change triggered research in this direction again.

In the extreme case, a new technology is developed with a certain (expected) factor endowment in mind in the first period. However, if the relative factor supply returns to old levels in the second period, the new technology might not be used at all, even though it appeared to be profitable during the first period. The history of hybrid automobiles brings this to the point. The first gasoline-electric hybrid automobile was invented already in 1901 by Ferdinand Porsche, but, although technologically outstanding, could not gain a relevant market share and hybrid automobiles were not further developed. Then during the oil crises in the 1970s, US manufacturer Briggs & Stratton developed a hybrid car that arrived at the market in 1980. However, since energy prices had declined again already, the concept remained unsuccessful. So even though the new technology seemed to be profitable during development, its time was over before it could reach the market. Only at the end of the 20th century, when the dangers of global warming became of world wide political concern and the need to cut down the use of fossil fuels in the future became apparent, the slow but steady triumph of hybrid automobiles began with the Toyota Prius, which was presented in 1997.

4 Direction of Technological Change

Even though the direction of technological change is not the primary interest of this paper, it is interesting to compare the results in this paper with those of the base model for directed technological change in Acemoglu (2002, 2007). Acemoglu defines technical change as being biased towards a certain input if it increases the relative marginal product of that particular factor compared to other inputs. For the production technology used in this paper, technological progress that is relatively biased towards input Q can be expressed as

$$\frac{\partial \frac{\partial x(A,Q,Z)/\partial Q}{\partial x(A,Q,Z)/\partial Z}}{\partial A} > 0. \tag{32}$$

Acemoglu (2002) finds that an increase in the supply of one input always leads to technical change that is biased towards this input.

In this model, the direction of technical change is determined by fundamental researchers, that choose the share coefficient ψ of the intermediate goods production function according to economy's expected relative supply of primary factors $\frac{\tilde{Q}_{2t}}{\tilde{Z}_{2t}}$. As the solution to the maximization problem in (25), the optimal ψ^* is given by

$$\psi^* = \frac{\tilde{Q}_{2t}}{\tilde{Q}_{2t} + \tilde{Z}_{2t}}, \tag{33}$$

hence ψ^* rises if the expected relative endowment $\frac{\tilde{Q}_{2t}}{\tilde{Z}_{2t}}$ increases and vice versa.

The relative marginal product of Q compared to Z in intermediate goods production is given by

$$\frac{\partial x(Q,Z)/\partial Q}{\partial x(Q,Z)/\partial Z} = \left(\frac{\psi}{1-\psi}\right)^{\frac{1}{\epsilon}} \cdot \left(\frac{Q}{Z}\right)^{\frac{1}{\epsilon}}, \tag{34}$$

hence it increases in ψ. Both results, together with the fact that a change in ψ always comes together with an increase in A, imply that technical progress is always biased towards the input that has become relatively more abundant, which is in line with Acemoglu (2002, 2007).

Notice however, that this finding is only true with respect to technological progress that results from fundamental innovations. In this paper, technological progress in the short run can result from fundamental innovations as well as from secondary development. A change in the relative factor supply will only result in directed technical progress, if a fundamental innovation is made. If, on the other hand, fundamental researchers are unsuccessful and technological progress results only from secondary development, only factor neutral technical change will be observed.

5 Simulation

To illustrate the quantitative significance of the model's implications, I simulate the model and study the effect of the relative changes in fossil fuel prices compared to renewable energy sources in the US from 1870 until today. Figures 4 and 5 display the development of fossil fuels (excluding nuclear energy) and renewable energy for primary energy consumption and the first purchase price for crude oil over time in the US.[13] It can be seen that the share of fossil fuels and renewables has remained fairly constant over the past 60 years with a slight shift towards renewables between the second half of the 1970s until the beginning of the 1980s and from 2005 onward. Similarly, the price for crude oil has been relatively stable with the exception of the time between 1910–1920, the two energy crises in the 1970s during which the real price increased dramatically, and a gradual increase from 2000 onward.

For the simulation, the period length is set to 10 years and the model's parameters are set to match the long term development of the US economy characterized in the spectral analysis by Korotayev and Tsirel (2010), which covers the time from 1871–2007. The authors estimate an average long-term cycle length of 50 years and an annual growth rate of 2.8%. Accordingly, the

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[13] The price for crude oil is used as a proxy for fossil fuel prices in the simulation.

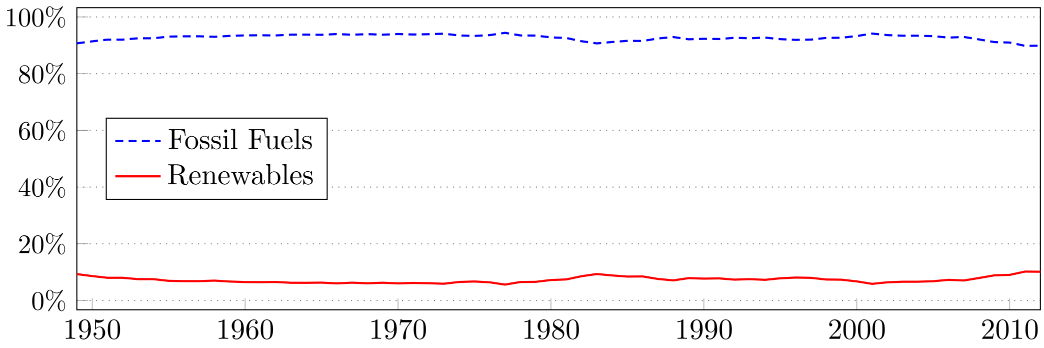

Figure 4: US primary energy consumption by source (Source: EIA)

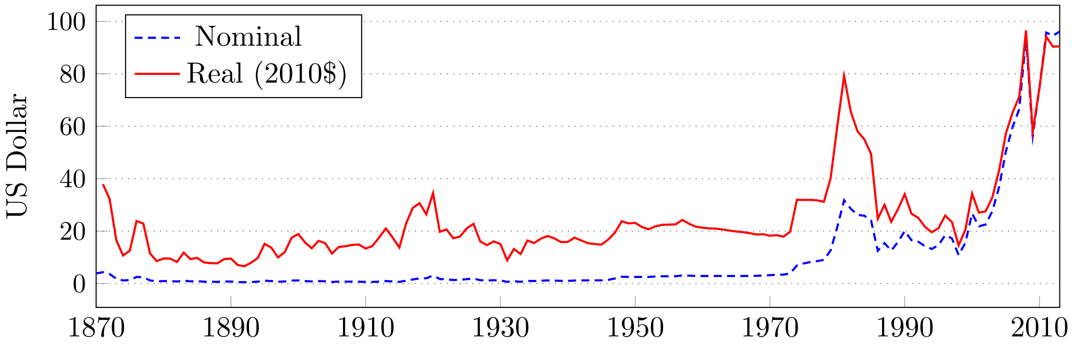

Figure 5: US crude oil first purchase price (Dollar per barrel) (Source: EIA)

productivity increase of a fundamental innovation is set to $\gamma = 3$.[14] The monopolist's share of the productivity gain of a new innovation ρ and the individual probability to be successful in fundamental research p have a very similar effect in the calibration, therefore one of them has to be held constant while the other is adjusted to yield the estimated growth rate. I set $p = 0.5$ and $\rho = 0.81$. The average annual growth rate during the upswing phase is estimated between 3.35–3.66 whereas for the downswing phase it is between 1.68–1.95. To match these values, I set the parameters for secondary development to $\mu = 1.30$ and $\phi = 0.75$. The elasticity of substitution between inputs is taken from Lanzi and Sue Wing (2011), who estimate a value of $\epsilon = 1.46$ for fossils fuels and renewables in the US energy sector. For the expectations about the future factor supply, I assume that the agents expect the supply to remain at its current level, so $\mathbb{E}_{1t}\left(\bar{Q}_{2t}\right) = \bar{Q}_{1t}$ and equally so for $\bar{Z}$.[15]

The simulation covers the period for which information on crude oil prices are available, that is from 1870 onward. Five additional periods are simulated upfront and then cut off to avoid the

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[14] This value is also used in Acemoglu and Cao (2010) for a fundamental innovation, based on the findings in Scherer (1986) and Freeman and Soete (1997).

[15] Since energy price hikes have typically arrived in the form of unforeseeable shocks during the 20. century, this assumption seems to be justified. Only lately, from the middle of the 1990s onward, a gradual increase of energy price can be noted, which should induce agents to adapt their expectations accordingly. Nevertheless, for the objective of this simulation, to illustrate the model's implications in terms of renewed fundamental research, the correct assumption for the agents' expectations about future energy prices has no great relevance. Even if the agents had perfect foresight, the reaction in terms of increased fundamental research would be similar, only the timing would vary.

influence of initial conditions; especially the fact that there is zero secondary development at the beginning of the simulation and hence the amount of fundamental research is at the maximum. For the presented results, the development of the economy has been simulated 1,000 times and the mean of the outcomes is reported. To eliminate the influence of extreme outcomes, the lowest and highest 10% of outcomes in terms of productivity at the end of the simulation period are dropped. I do the complete simulation in two versions: one without changes in the supply of crude oil, which serves as a benchmark, and one where the price changes given in Figure 5 are taken into account. To be in line with the model, these price changes have been translated into changes in the (inelastic) supply of crude oil while the supply of renewables has been held constant.

Figure 6 displays the development of the simulated economy without crude oil price changes taken into consideration.[16] The upper part shows the share of fundamental researchers and the lower part gives the annual rate of productivity growth. It turns out, that the share of fundamental researchers falls over time until it becomes zero at the end of the simulation period. Accordingly, productivity growth diminishes constantly over time with only minor fluctuations.

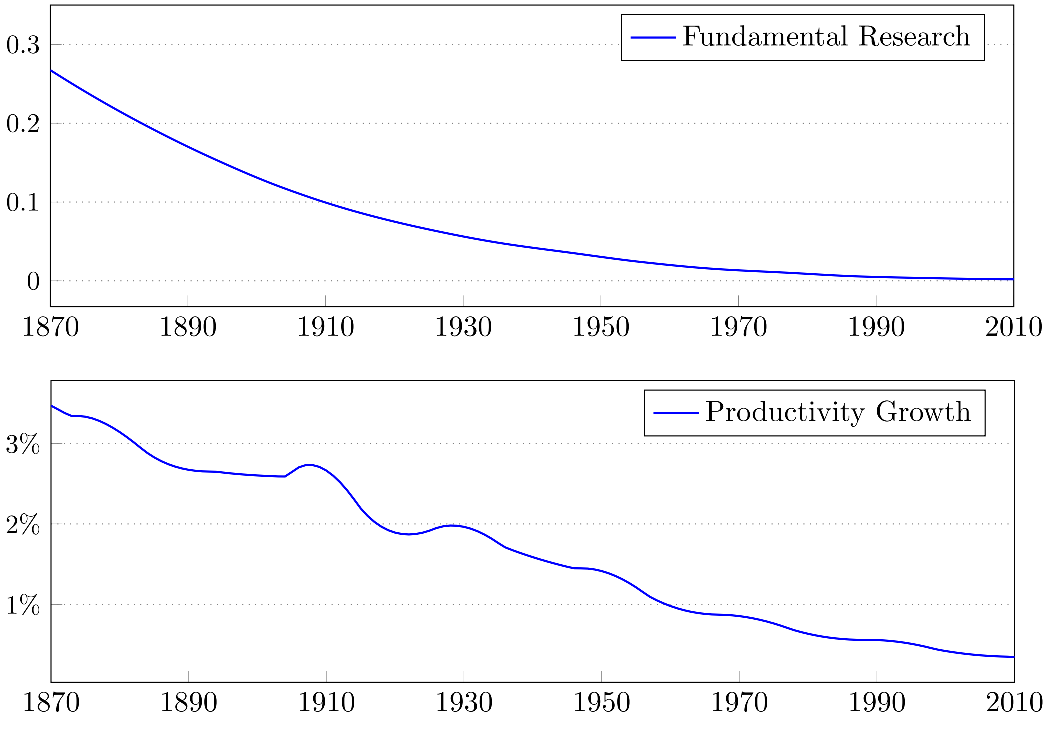

Figure 6: Simulation without price changes

By contrast, Figure 7 depicts the simulation results when the changes in the crude oil price are included in the simulation.[17] It turns out that in this case, fundamental research and productivity growth do not decline over time and that they follow the changes in the supply of

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[16] To provide smooth curves, annual numbers are interpolated from the 10-year-period raw data.

[17] To take the length of a simulation period into account, 10-year rolling averages of crude oil prices have been used.

crude oil given in Figure 5. After some initial fluctuations, the crude oil price remains fairly constant until 1910. Accordingly, the share of fundamental researchers and productivity growth declines in the simulation. From 1910 onward, the crude oil price starts to increase substantially and more than doubles around 1920 compared to average value of the previous period. In the simulation, these price changes nearly double the share of fundamental researchers in 1920 compared to 1910 which leads to increased productivity growth. After the peak, the crude oil price becomes fairly stable again. The next price hike takes place around 1950 which is mirrored in the simulation by a reinforcement of fundamental research and a higher productivity growth rate. This is followed by the double oil crisis during the 1970s, which again is reflected in the simulation by a higher share of fundamental research; the same is true for the price increase from 2000 onward.

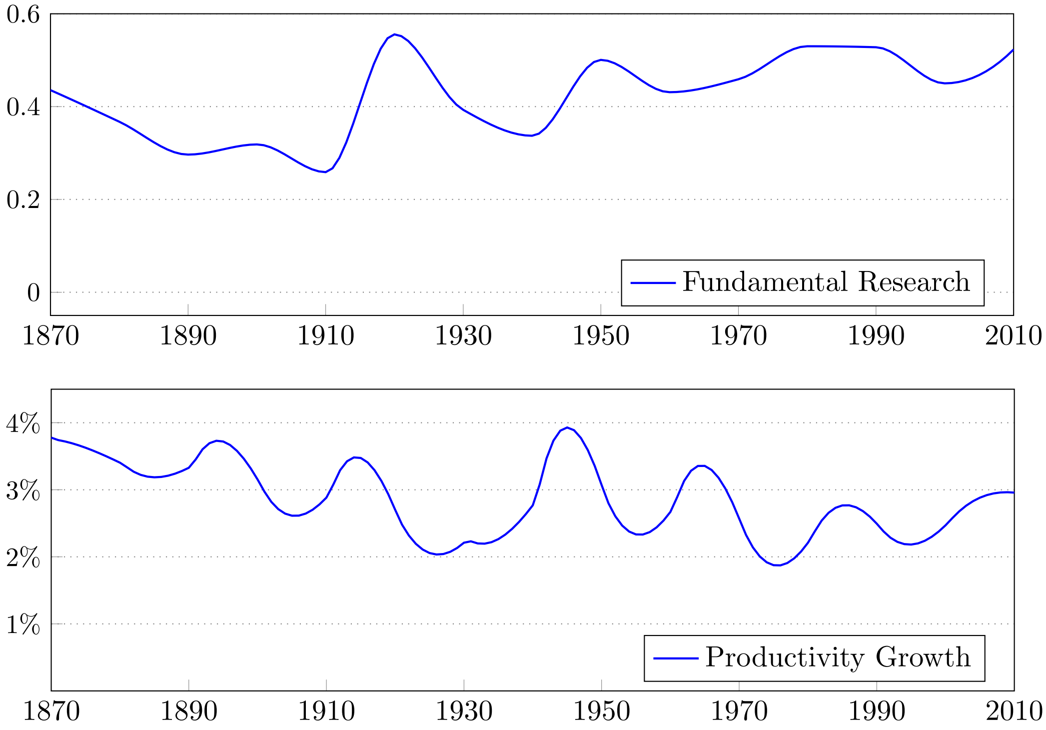

Figure 7: Simulation with changes in crude oil price

The simulations show that real world factor price changes have a strong influence on the incentives for fundamental research. While fundamental research eventually ceases over time and path dependence lets the simulated economy become trapped in a technological lock-in in the case with no price changes, the version that took the changes in crude oil prices into account could avoid this fate. Although fundamental research declined during the phases with stable prices, the substantial changes in the oil price that occurred several times during the simulation period stimulated fundamental research and led to new fundamental innovations, so that neither research nor productivity growth ceased in the long run. These results indicate that the model's implications are quantitatively important and significantly influence real world economic development.

6 Conclusions

Path dependence denotes the fact that the trajectory of technological development is shaped by previous decisions and outcomes which can lead to the dominance of certain technologies in spite of the availability of better alternatives. However, this dominance is sometimes overcome when changes in the environment induce new innovations and make alternative technologies more attractive.

In this paper, I develop a model that captures the origins of path dependence and also introduces a mechanism of induced innovation which allows to escape from technological lock-in. Due to imperfect spillovers of secondary development, new technologies can be inferior in comparison to dominant existing technologies and the economy becomes trapped in a technological lock-in. However, since fundamental innovations can be directed to favor a particular input factor, changes in the relative supply of primary factors increase the productivity gain of a new technology and induce research to overcome the lock-in.

The model is able to explain the long waves of economic development, where supply changes trigger a new growth cycle. A simulation of the model using the changes of crude oil prices indicates, that the model's implications are quantitatively relevant. With its main finding, that changes in the supply of primary factors can induce innovative activity and stimulate technological progress, the paper also provides a new rationale for policies that aim to increase social welfare and reduce environmental damage by the use of Pigouvian taxes or pollution permits.

For future work, the model could be extended in a number of ways. First, the assumption of zero spillovers of secondary development between fundamental technologies could be relaxed to allow partial spillovers as in Redding (2002). Obviously, some of the human capital and efficiency improvements can be also used for other technologies as well. For the keyboard layout example, it is documented that QWERTY-trained typists need less time to adapt to the Dvorak layout than untrained people. Also the development of alternative-drive vehicles benefits from many of the improvements of gasoline cars over the last century. Second, the adjustment to a new relative supply regime, which is done within one fundamental innovation, could be limited in such a way that it takes a number of fundamental innovations until the economy has completely adapted to the new environment. This would move the model closer to the typical models of directed technological change, where these adjustments take place gradually. Third, the model could be easily extended to use a larger number of primary factors. With a nested intermediate goods production function, different elasticities of substitution can be taken into account. A change in the supply of any of these factors could than induce new research. Such an extension could be especially helpful for empirical work.

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