



*Citation for published version:*

Schaefer, A, Schiess, D & Wehrli, R 2014, 'Long-term growth driven by a sequence of general purpose technologies', *Economic Modelling*, vol. 37, pp. 23-31. <https://doi.org/10.1016/j.econmod.2013.10.014>

*DOI:*

<https://doi.org/10.1016/j.econmod.2013.10.014>

*Publication date:*

2014

*Document Version*

Peer reviewed version

[Link to publication](#)

*Publisher Rights*

CC BY-NC-ND

## University of Bath

### General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

### Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

# Long-Term Growth Driven by a Sequence of General Purpose Technologies

Andreas Schaefer (University of Leipzig) Daniel Schiess (ETH Zurich)<sup>†</sup>  
Roger Wehrli (ETH Zurich)

We present a Schumpeterian model of endogenous growth with General Purpose Technologies (GPTs) that captures two important historical stylized facts: First, from the beginning of mankind until today GPTs are arriving at an increasing frequency and, second, all GPTs heavily depended on previous technologies. In our model, the arrival of GPTs is endogenous and arises stochastically depending on the currently available applied knowledge stock. This way of endogenizing the arrival of new GPTs allows for a model which is more in tune with the historical reality than the existing GPT models.

*Keywords: Schumpeterian growth; research and development; general purpose technologies*

*JEL classification: O11, O33, O41*

---

\*We thank Lucas Bretschger, Maik Schneider, Thomas Steger, and two anonymous referees for helpful comments and constructive suggestions.

<sup>†</sup>Corresponding author: Center of Economic Research at ETH Zurich, ETH Zurich, ZUE F 9, CH-8092 Zurich, Switzerland. Phone +41 44 632 86 49, Fax +41 44 632 13 62, Email: dschiess@ethz.ch

# 1 General Purpose Technologies and Long-Term Growth

A small number of ground-breaking inventions arriving in ever decreasing time intervals can be identified as important drivers of long-term economic growth: In early human history millennia lay between transforming innovations such as the domestication of plants and animals or the Bronze Age and the Iron Age. Later, the era of the industrial revolution witnessed the rise of the steam engine and production in large-scale factories, followed by the birth of railways and the steam ship in the course of only one century. Finally, current levels of welfare would hardly be possible without the introduction of personal computers and the rapid spread of the Internet usage within a few decades.

The view that such breakthrough technologies or “General Purpose Technologies”, or GPTs, can be seen as true “engines of growth” has been shaped by Bresnahan and Trajtenberg (1995): They characterize GPTs as being radical innovations in the sense that they are “... characterized by the potential for pervasive use in a wide range of sectors and by their technological dynamism. As a GPT evolves and advances it spreads throughout the economy, bringing about and fostering generalized productivity gains.” Furthermore they emphasize that GPTs are “enabling technologies”, which give rise to new opportunities instead of offering complete, final solutions. As a matter of illustration, they present a static model where a monopolistic owner of the GPT interacts with corresponding application sectors.<sup>1</sup>

In the course of this paper we present a model where long-run growth is driven by a sequence of GPTs. Our model captures two stylized facts, which looking at the evolution of GPTs in history, immediately spring to mind: First, the time interval between the arrival of new GPTs has become ever shorter. This point can of course, at least partly, be seen as a result of the ever increasing pool of accumulated knowledge. Second, new GPTs are usually based on previously invented technologies and existing knowledge. Taking the Internet as an example, its invention would not have been possible without a multitude of previous inventions ranging from the computer to electricity. We achieve in modelling these stylized facts by extending our own model of Schumpeterian growth and GPTs, as presented in Schiess and Wehrli (2008). While in our previous model long term growth is driven by exogenously arriving new GPTs, we now endogenize the arrival of new GPTs. Specifically, the probability that a new GPT arrives depends on the amount of previously accumulated applied knowledge. This allows us to model long-term growth as driven by a sequence of GPTs which, due to the rising stock of applied knowledge, arrive at ever shorter time intervals. Furthermore, we model economic cycles within the lifetime of a single GPT, assuming that the economic impact of such a new technology decreases

---

<sup>1</sup>In this model the assumption that the GPT is provided by a monopolist can, not surprisingly, result in too little research being performed in the sectors applying this technology.

over time.

Before we elaborate on the empirical regularities in the arrival of new GPTs which we address in our model, we turn to a brief survey of the previous literature on GPTs.

## 1.1 Previous Literature: Short-Term Cycles Caused by GPTs

While GPTs are widely seen as a main driving force of long-term economic growth, a majority of the literature on GPTs is concerned only with the lifetime of a single GPT, with a strong focus on the first phase after its introduction. This tendency is without doubt motivated by the goal of finding an explanation for the Solow paradox, according to which initially the already ubiquitous computers did not have any impact on productivity statistics. The phenomenon of a new GPT taking decades before having a major impact on economic aggregates is stated for example by David (1990), taking the example of electricity and the computer. Basu, Fernald and Kimball (2006) show in an empirical study, that while technological improvements are beneficial in the long run, they can have contractionary effects in the short run. Similarly, Jacobs and Nahuis (2002) present a model whereby the introduction of a new GPT leads to a decrease in output in the short run. This is caused by high-skill workers being drawn away from output production due to the sudden increase in research productivity induced by the new GPT. According to Helpman and Trajtenberg (1998a) a new, exogenously arriving GPT cannot be put to a productive use in the final goods sector until a sufficient number of complementary components needs to be invented first (for example software in the case of computers). As this process requires resources to be moved from the final goods sector to the R&D sector, this results in a temporary decline in measured output. As soon as a sufficient number of components has been developed, the new GPT can be used in the production of the final good, leading to output growth picking up speed again.<sup>2</sup> At this point it is also important to note that the hypotheses of productivity slow-downs after the arrival of new GPTs is not that strong. Carlaw and Lipsey (2011), p. 566 state: "The introduction of a new GPT is sometimes, but not always, associated with a slowdown in the rates of growth of productivity and national income"

---

<sup>2</sup>In Helpman and Trajtenberg (1998b) they additionally model how the diffusion of a new GPT to the various sectors of the economy can prevent it from having an immediate impact on output growth. Eriksson and Lindh (2000), argue that based on Helpman and Trajtenberg (1998a), the initial adverse impact of a new GPT can be mitigated, if components that were built for the old GPT can partially be used even after the arrival of a new GPT. Aghion and Howitt (1998a) retain a component building phase, but add a template-building phase coming into effect immediately after the arrival of a new GPT: As these templates are designed by specialized labor without any other uses, there is no measured impact on output during this initial phase. See Wehrli and Saxby (2008) for a more in-depth literature review.

## 1.2 Previous Literature: GPT Models of Long-Term growth

Despite the fact that GPTs are widely seen as a main driving force of economic growth, models on GPT-driven long-term growth are relatively scarce: Aghion and Howitt (1998b) present a Schumpeterian model where long-term growth is driven by a sequence of innovations with an arrival rate which is proportional to the amount of labor devoted to research. While this model does not directly apply the concept of GPTs it is nevertheless a starting point when trying to explain growth driven by an endogenously created series of innovations.

Explicitly modeling GPTs, Carlaw and Lipsey (2006) developed a model with a sequence of GPTs arriving one after the other, with only one being active in any given period. In their model the arrival of a new GPT is governed by a constant random variable, hence the expected time interval between two GPTs remains always the same. Meanwhile, there is a variation in the size of the impact of a new GPT rising from the endogenously created pool of basic knowledge.

Van Zon and Kronenberg (2003) present a model where again long-term growth is driven by the arrival of new GPTs. While the expected time interval between the arrivals of new GPTs is again fixed, their model allows for different GPTs being active simultaneously. In a further refinement of their baseline model, van Zon and Kronenberg (2006) evaluate different tax policy measures in a scenario where long-run growth is driven by GPTs which are based either on carbon fuels or on non-carbon fuels. The probability of arrival of these GPTs is governed by the amount of currently performed basic R&D and they furthermore allow for various GPTs existing simultaneously.

## 1.3 Stylized Fact 1: Decreasing Time Intervals between GPTs

While the question which technologies qualify as a GPT cannot be answered in a conclusive way,<sup>3</sup> the fact that such transforming technologies arrive at an ever faster pace seems to be undeniable. Taking the list of historical GPTs compiled by Carlaw and Lipsey (2006) as shown in Table 1 as a point of reference, it becomes clear that the interval between the arrival of individual GPTs has steadily decreased in the course of history. This general trend is described by Carlaw and Lipsey (2008, p. 131-133) as follows: human existence has been accompanied by the introduction of new GPTs but the rate of innovation of new GPTs has been accelerating drastically in the 20th century. In the eighteenth century there are two important GPTs, four in the nineteenth century, and seven in the twentieth.

Despite this strong empirical pattern of an acceleration in the arrival rate of new GPTs in the course of history, none of the previously mentioned models

---

<sup>3</sup>see Lipsey, Carlaw and Bekar (1998) for further elaborations.

No.	GPT	Date
1	Domestication of plants	9000 - 8000 BC
2	Domestication of animals	8500 - 7500 BC
3	Smelting of ore	8000 - 7000 BC
4	Wheel	4000 - 3000 BC
5	Writing	3400 - 3200 BC
6	Bronze	2800 BC
7	Iron	1200 BC
8	Waterwheel	Early medieval period
9	Three-masted sailing ship	15th century
10	Printing	16th century
11	Steam engine	Late 18th to early 19th century
12	Factory system	Late 18th to early 19th century
13	Railway	Mid 19th century
14	Iron steamship	Mid 19th century
15	Internal combustion engine	Late 19th century
16	Electricity	Late 19th century
17	Motor vehicle	20th century
18	Airplane	20th century
19	Mass production, continuous process, factory	20th century
20	Computer	20th century
21	Lean production	20th century
22	Internet	20th century
23	Biotechnology	20th century
24	Nanotechnology	Sometime in the 21st century

Table 1: Historical GPTs as listed in Lipsey et al. (2006, p. 132)

considers this fact: On one hand, the models on the impact of new GPTs on the course of a single economic cycle are by definition not concerned with a sequence of GPTs. On the other hand, the presented models on long-term growth driven by a sequence of GPTs either assume either fixed time intervals between the arrival of new GPTs or a stochastic pattern with no long-term trend in either direction.

#### 1.4 Stylized Fact 2: GPTs Based on Current Stock of Applied Knowledge

Sir Isaac Newton is frequently quoted, for example by Scotchmer (1991), to illustrate that even the greatest minds in history depend on already existent knowledge: “If I have seen far, it is by standing on the shoulders of giants.” Just as non-radical inventions more often than not build on previously existing knowledge, all GPTs had its origins to a certain extent in already present technologies.

Even a cursory glance at some of the GPTs in the past shows this very clearly: The invention of moveable type printing by Johannes Gutenberg in the second half of the 15th century dramatically changed the way how both secular and re-

ligious knowledge was disseminated. Gutenberg made the huge step away from previous methods of reproduction of written information (such as woodblock printing and the production of manuscripts on parchment) by combining a multitude of existing technologies, instead of starting from scratch: The moveable types were derived from stamps used by jewelers to mark their products, while the printing press itself was modeled on the wine press. Paper already existed in his time and while not suited very well for handwritten volumes, turned out to be ideal for this new application.

The same reasoning holds true for the steam engine, which was invented by James Watt towards the end of the 18th century. Previously steam has already been used to drive atmospheric engines, such as the Newcomen engine. Again a large part of James Watt's genius laid in combining a number of already existent technologies: His steam engine still maintained the basic principle of using steam to move a piston within a cylinder, but while previous engines used atmospheric pressure to drive the power stroke, his engine used steam for this vital step.<sup>4</sup> Not only did this invention heavily build on previously existing technologies, it also facilitated the birth of subsequent GPTs such as the iron steam ship, railways and ultimately the internal combustion engine and the automobile.

As a final example, the invention of the computer would have been impossible without another GPT, electricity, being already in existence. It also relied on previous practical inventions: These date back as far as the idea of storing information on punched cards, as pioneered in the form of the Jacquard loom, and ideas from the theoretical foundations on computing laid out by Alan Turing in the 1930s. Similar musings could, to various degrees, be done for all GPTs in history.<sup>5</sup>

The remainder of this paper is structured as follows: In Section 2 we will present our theoretical model of GPT-driven endogenous growth. The main implications of our model and the results of our simulations will be shown in Section 3, while we conclude and offer some outlook in Section 4.

---

<sup>4</sup>Another major improvement was that, while in earlier machines steam was condensed inside the cylinder, he added a separate condenser to cool down the steam exhausted from the piston. These two modifications to previous steam engines allowed the Watt engine to extract much larger horsepower from a machine of a given size with a significantly larger fuel efficiency.

<sup>5</sup>The notion that a higher amount of available knowledge leads to a higher productivity of research has also been contemplated by Romer (1990), p.883f. "*The engineer working today is more productive because he or she can take advantage of all the additional knowledge accumulated as design problems were solved during the last 100 years.*"

## 2 Long-Term Growth Driven by a Sequence of GPTs

We present a Schumpeterian model of long-term growth in a quality-ladder framework which is a discrete-time version of the model presented in Schiess and Wehrli (2008).<sup>6</sup> Our model has a unique combination of features: On one hand, it focuses on the long-term evolution of the economy. On the other hand, we endogenize the arrival of new GPTs, whereby the probability of discovering a new GPT positively depends on the currently available stock of applied knowledge. Together, these characteristics of our model allow for a more realistic representation of some aspects of the historical development of GPTs: Our model describes long-term sustained growth through the arrival of successive GPTs which arrive endogenously, due to the present stock of applied knowledge. Partly as a result of this, we can account for the fact that the time interval between the arrival of new GPTs has constantly decreased over the course of history.

### 2.1 Model Overview

There are three sectors present in our model: The final goods sector, the intermediate goods sector and consumption. Final good producers demand intermediates. In each period  $t$ , there exists a fixed number,  $N$ , of varieties of intermediates indexed by  $j$ , where  $j \in \{1, 2, 3, \dots, N - 1, N\}$ . Each type of intermediate good,  $j$ , has a quality ladder along which quality improvements occur. The distinguishing feature of Schumpeterian growth models is that, when an intermediate of type  $j$  is improved, the new intermediate will displace the old one and eliminate monopoly profits of incumbents (process of creative destruction). Essentially, the turn-over of monopoly profits from incumbents to new innovators, i.e. the duration time of a monopoly position, depends on the probability of research success. The probability of research success in turn is positively influenced by the amount of resources allocated to R&D, and the level of the GPT, but negatively affected by the achieved level of quality improvements, i.e. it becomes increasingly difficult to innovate. The arrival of a new GPT depends on the amount of cumulated knowledge reflected by the aggregate amount of quality improvements in the economy. The efficiency of a new GPT increases slowly after its arrival while the speed of this increase depends on applied knowledge about this GPT in R&D, that is the number of quality improvements that have been achieved under this new GPT. Since this experience is zero after the arrival of a new GPT, the evolution of the efficiency of this GPT depends on the complementarity between past knowledge and the new GPT. As the efficiency of an existing GPT increases the probability of research success, while output growth depends positively on the number of quality improvements, the latter

---

<sup>6</sup>The original model, contrary to the present model, focuses on the time frame immediately before the arrival of a new GPT, whereby the economy before and after this transition phase is characterized by steady-state behavior.



is positively associated to the level of the GPT.

The aggregate amount of final goods can be used for either consumption  $C$ , as an input  $Z$  needed to perform R&D, or for intermediate goods  $X$ . An amount of  $Y_i$  of final good  $i$  is produced using a constant technology  $A$  and labor  $L_i$  according to the following production function.

$$Y_i = AL_i^{1-\alpha} \sum_{j=1}^N (\tilde{X}_{ij})^\alpha \quad (1)$$

where  $0 < \alpha < 1$ .

The number of varieties of intermediate goods is given by the fixed number  $N$ . The fact that each of these varieties of intermediate goods have a specific quality level is reflected in the following equation.

$$\tilde{X}_{ij} = q^{\kappa_j} X_{ij} \quad (2)$$

$X_{ij}$  is the physical amount of an intermediate good, while  $q^{\kappa_j} > 1$  is the highest quality in which this intermediate good is currently available. The current level of this intermediate good is given by  $\kappa_j$ .

The final goods firms, operating under perfect competition, only demand the highest quality available in each sector according to the following aggregate demand equation:<sup>7</sup>

$$X_j = L(A\alpha q^{\alpha\kappa_j} / P_j)^{1/(1-\alpha)} \quad (3)$$

Intermediate goods firms hold a monopoly on their goods, selling them to the final goods sector with a monopoly markup, whereby they set the price as  $P_j = \frac{1}{\alpha}$ . Faced with the aggregate demand function (3), intermediate goods firms provide the following amount of an intermediate good  $X_j$ :

$$X_j = LA^{\frac{1}{1-\alpha}} \alpha^{\frac{2}{1-\alpha}} q^{\kappa_j \frac{\alpha}{1-\alpha}} \quad (4)$$

Aggregating across all final goods firms and assuming a fixed aggregate amount of labor  $L$  we get the following amount of aggregate amount of intermediate goods  $X$  and of final goods  $Y$ :

$$X = A^{\frac{1}{1-\alpha}} \alpha^{\frac{2}{1-\alpha}} LQ \quad (5)$$

---

<sup>7</sup>See Schiess and Wehrli (2008) for a more detailed description on the derivation of the equations in this subsection.

$$Y = A^{\frac{1}{1-\alpha}} \alpha^{\frac{2\alpha}{1-\alpha}} LQ \quad (6)$$

The aggregate quality index  $Q$  is given by the following equation:

$$Q \equiv \sum_{j=1}^N q^{\kappa_j \alpha / (1-\alpha)} \quad (7)$$

By adding up the highest available quality in each intermediate goods sector  $Q$  gives an accurate representation of the current technological level of the economy. For this reason  $Q$  will later be used as an indicator of the currently available applied knowledge stock.

Intermediate goods firms can engage in in-house R&D in order to invent a type of intermediate good of an even higher quality. If such a firm succeeds in inventing a new quality in a certain sector, it will hold the monopoly on this good, displacing the previous monopolist. In a Schumpeterian fashion, it will hold this monopoly (therefore reaping monopoly profits by selling the intermediate good to the final good sector according to the demand function in each period) until it is displaced by yet another successful intermediate goods firm. This process of continuous inventions leads to an increase in the quality of available goods, thereby driving economic growth.

We consider a small open economy which faces a constant interest rate  $r \geq 0$  and keep the individual household's problem deliberately simple, in the sense that individuals are risk-neutral and indifferent between future and present consumption, such that households maximize

$$U(t=0) = \sum_{t=0}^{\infty} \beta^t c(t), \quad (8)$$

where  $0 < \beta < 1$  is the discount factor and  $\frac{1-\beta}{\beta}$  is the rate of time preference which, in equilibrium, must be equal to the interest rate, such that  $\beta = \frac{1}{1+r}$  for all  $t$ .

Ultimately the consumption sector is used to close the model, once equilibrium production and R&D expenditures are determined.

## 2.2 Determinants of R&D Expenditures

Denote by  $p(\kappa_j, t)$  the probability of a successful innovation in sector  $j$ , in period  $t$ , where  $\kappa_j$  denotes the highest available quality in sector  $j$ . In period  $t$ , potential innovators expend a flow of resources,  $Z(\kappa_j, t)$ , in order to attempt to

invent an intermediate good with an even higher quality  $\kappa_j + 1$ . Plausibly, we assume that the probability of success,  $p(\kappa_j, t)$ , depends positively on  $Z(\kappa_j, t)$  such that more research expenditures will shorten the duration time of current monopolists. To find the optimal amount of  $Z(\kappa_j, t)$  two main aspects are crucial: First we need to consider the probability of having a research success in relation to the R&D expenditures. Second, we need to build expectations on the payoff in case of having a research success.

### 2.2.1 Probability of a Research Success

The probability of a research success is given by the following equation:

$$p(\kappa_j, t) = Z(\kappa_j, t)\phi(\kappa_j)B(n, t) \quad (9)$$

This expression captures a multitude of effects: Of course a higher amount of R&D expenditures  $Z(\kappa_j, t)$  directly increases the probability of having a research success. Furthermore, the currently active GPT positively influences the probability of having a research success through its level of productivity in R&D,  $B(n, t)$ , where  $n$  represents the vintage of the GTP. This is modeled according to the notion that GPTs do not directly influence the efficiency of final goods production, but rather allow for an increase in R&D efficiency (see for example Jacobs and Nahuis, 2002). The evolution of  $B(n, t)$  over the course of a single GPT,  $n$ , and over a succession of GPTs will be presented at a later stage. Finally  $\phi(\kappa_j)$  is a function, which captures the difficulty of doing R&D especially in relation of the quality the R&D firm wants to improve upon. The functional form of  $\phi(\kappa_j)$  is specified as follows:

$$\phi(\kappa_j) = \frac{1}{\zeta} q^{-(\kappa_j+1)\alpha/(1-\alpha)} \quad (10)$$

The difficulty of performing R&D in a sector with the current quality level  $\kappa_j$ , is therefore determined by two factors: First, there is a constant cost parameter  $\zeta$ . Second, there is an increase of difficulty of R&D, which rises with the quality of the variety of the intermediate good it wants to improve upon, given by the expression  $q^{-(\kappa_j+1)\alpha/(1-\alpha)}$ .

### 2.2.2 Endogenous Arrival of new GPTs

Apart from the difficulty to achieve further quality improvements as captured by  $\phi(\kappa_j)$ , and the amount of R&D performed in a sector  $Z(\kappa_j, t)$ , the behavior

of the GPT level as given by  $B(n, t)$  needs to be determined in order to have a full description of the factors influencing the probability of having a research success. The evolution and the arrival of GPTs drive the probability of research success and therefore the duration of monopoly power of incumbents. With our approach we seek to capture the following stylized facts on the course of an individual GPT and the arrival of new GPTs in history: (see Carlaw and Lipsey, 2011):

- (i) The efficiency of a new GPT evolves slowly
- (ii) The number of GPTs increases

In order to capture these facts, we model the evolution and the arrival of a new GPT,  $n + 1$ , as follows: At the moment, when a new GPT arrives,  $B(n + 1, t)$  starts off with a level of

$$B(n + 1, t) = \bar{B}\tilde{q}(t)/Z(t - 1),^8 \quad (11)$$

where  $\bar{B} > 0$  represents a positive scale parameter and  $\tilde{q}$  denotes an index of applied knowledge that is available for the application of the GPT, with

$$\tilde{q}(t) = (\tilde{Q}(n + 1, t)/Z(t - 1))^\delta (\tilde{Q}(n, t)/Z(t - 1))^{1-\delta} \quad (12)$$

and  $\tilde{Q}(n + 1, t) + \tilde{Q}(n, t) = Q(t)$ .

The aggregate quality index  $Q$  at date  $t$  consists out of all quality improvements achieved under all previous GPTs in history,  $\tilde{Q}(n, t)$ , and the experience subject to the new arrived GPT, reflected by the overall number of quality improvements subject to the new GPT,  $\tilde{Q}(n + 1, t)$ . The level of applied knowledge available for the new GPT,  $\tilde{q}$ , depends on the degree of complementarity between previous knowledge and knowledge accumulated under the new GPT as captured by  $\delta$ . If  $\delta = 1$ , past experience is entirely useless. If  $\delta = 0$ , the experience with the new technology would be useless such that  $\delta = 0$  is meaningless. Therefore, economically meaningful degrees of complementarity between past and present acquired knowledge are defined by  $0 < \delta \leq 1$ . Since after the introduction of a new GPT the experience with this GPT in R&D is zero, i.e.  $\tilde{Q}(n + 1, t) = 0$ , the initial level of a new GPT reads

$$B(n + 1, t) = \bar{B}(\tilde{Q}(n, t)/Z(t - 1))^{1-\delta}, \quad (13)$$

and depends obviously on the amount of acquired knowledge until the date of its arrival and how useful this knowledge for the implementation of the new

---

<sup>8</sup>The division by aggregate research expenditures measures economically its efficiency as compared to the achieved quality improvements. Technically this scale adjustment prevents, moreover, the initial value of a new GPT to grow to infinity.

GPT is, as reflected by  $\delta$ , i.e. for  $\delta = 1$ , there is a structural break after the arrival of  $n + 1$  in the sense that previous acquired knowledge is not helpful for the application of the new GPT, such that this GPT starts at its minimum possible level  $B(n + 1, t) = \bar{B}$ .

The next feature is the evolution of  $B(n + 1, t)$  over time. Since the efficiency of the new GPT evolves slowly over time, we suggest a logistic function of the following form (see also Carlaw and Lipsey, 2011 for similar assumptions in a different frame)

$$B(n + 1, t) = B(n + 1, t - 1) + \frac{B^{max}}{1 + \exp[-\tilde{k}B^{max}(\tilde{q}(t) - k)]\left[\frac{B^{max}}{\bar{B}} - 1\right]}, \quad (14)$$

with  $\bar{B}, B^{max}, k, \tilde{k}$  being positive constants.

The second term in the above equation is a logistic function in the level of applied knowledge available for the new GPT,  $\tilde{q}(t)$ . This function shifts upwards according to level of the GPT in the previous period,  $B(n + 1, t - 1)$ . The parameter  $B^{max}$  determines the upper limit of the GPT while  $\bar{B}$  determines the lower limit. The parameter  $k$  triggers the necessary amount of applied knowledge available for the new GPT,  $\tilde{q}$ , in order to achieve an increase in  $B$ .<sup>9</sup> The slope of Eq. (14) in between the lower and the upper bound is determined by  $\tilde{k}$  and triggers therefore the effect of knowledge on the increasing part of this s-curve. More quality improvements under the new GPT means that this technology diffuses into the economy and the research sectors start to accumulate experiences with this technology. This will increase the level of the GPT and generate even more quality improvements since the probability of research success is increasing in the level of the GPT.

Accordingly, the most recent GPT evolves according to the following set of equations:

$$B(n + 1, t) = \begin{cases} B(n + 1, t - 1) + \frac{B^{max}}{1 + \exp[-\tilde{k}B^{max}[\tilde{q}(t) - k]]\left[\frac{B^{max}}{\bar{B}} - 1\right]} & \text{if } a(t - 1) = 0 \\ \bar{B}(\tilde{Q}(n, t)/Z(t - 1))^{1-\delta} & \text{if } a(t - 1) \geq 1 \end{cases} \quad (15)$$

$a(t - 1)$  is drawn by an endogenous Poisson process with the mean  $\lambda(t)$  of the Poisson distribution given by:

$$\lambda(t) = \varphi B(n, t - 1) \quad (16)$$

where  $0 < \varphi < 1$ .

This specification of the Poisson distribution captures the following stylized facts on the long-term evolution of GPTs: The fact that the arrival of new GPTs is commonly facilitated by the amount of currently available applied

---

<sup>9</sup>Since (14) corresponds graphically to a s-curve, the length of the lower bound depends on the size of  $k$ , i.e. the larger  $k$  the larger the amount of  $\tilde{q}$  in order to achieve increases in  $B$ .

knowledge which triggers the maturity of the current GPT is accounted for by the inclusion of level of the GPT  $B(n, t-1)$  in this equation which remember is a function of  $\tilde{q}$ . Therefore a larger amount of applied knowledge increases the probability of a new GPT arriving. Contrarily, the fact that the productivity of a GPT is low after its arrival, leads to an initial drop in  $\lambda$  upon the arrival of a new GPT. Afterwards, as  $B(n, t-1)$  is rising in the level of acquired knowledge,  $\lambda$  rises again. This behavior is consistent with features of other GPT models, where the arrival of a new GPT initially binds significant R&D resources for exploring the possibilities offered by the new GPT. In the example in Carlaw and Lipsey (2006), the arrival of a new GPT leads to a drop in basic research (which in their model is aimed at inventing new GPTs) which picks up speed again over the lifetime of the GPT.

The behavior of  $\lambda$  over time can be nicely illustrated by deriving the expected time until the arrival of a new GPT. This is approximately given by the waiting time distribution of the above defined Poisson process with rate  $\lambda$ . The time  $T$  one must wait until the next GPT arrives is given by the following cumulative distribution:<sup>10</sup>

$$F(t) = P(T \leq t) = 1 - e^{-\lambda(t)} \quad (17)$$

By differentiating equation (17) we get a density function with mean:

$$E(T) = \frac{1}{\lambda} \quad (18)$$

And finally together with equation (16):

$$E(T) = \frac{1}{\varphi B(n, t-1)} \quad (19)$$

As can be easily seen the higher the level of  $B$ , the shorter is the expected waiting time for a new GPT. On the other hand there is also a cyclical component during the lifetime of an individual GPT: While initially, there is an increase in the expected waiting time, it gets gradually lower in the course of a GPT, as the current  $B(t)$  increases to its maximum value.

### 2.2.3 Expected Profits

Another main determinant of the amount of R&D performed is the expected profit in case of a research success. We will first present how R&D firms build their expectations on the expected profit in case of a research success  $E[V(\kappa_j + 1)]$ . In determining the amount of information the R&D firms have, we basically follow the line of reasoning of Carlaw and Lipsey (2006): They argue that it is impossible for agents to predict either the development of a single GPT or the exact time of arrival of a new GPT. Due to this uncertainty, the

---

<sup>10</sup>This equation can be derived by using the fact that  $P(T > t) = e^{-\lambda t}$  following from the Poisson distribution and the use of the complement rule.

assumption of perfect foresight taken in the majority of growth models cannot be sustained. They therefore propose two possible ways how agents maximize their utility in each period recursively: One approach would be that agents are not forward looking at all, therefore only considering the marginal products of the current period and maximizing only their current profit. Another possibility is that, while agents are forward looking, they simply assume that marginal products across all sectors remain constant at the level currently observed and maximize accordingly over an infinite time horizon. While Carlaw and Lipsey (2006) choose the first approach for their own model, we use the second approach: Individuals maximize in every period their outcome based on the values of this specific period since we are assuming that they are forward looking but cannot foresee future changes, i.e. they believe that the current marginal productivity of research does not change over time. In the following period the individuals realize that the productivity has changed and readjust their decision. Concretely applied to the R&D sector in our model this basically means that R&D firms assume that current equilibrium levels of the interest rate  $r$  and of the probability of having a research success  $p$  apply for the whole future.<sup>11</sup> The profit flow per period an innovator possessing the leading-edge technology is given by:

$$\pi(\kappa_j) = \bar{\pi} q^{\frac{\kappa_j \alpha}{1-\alpha}} \quad (20)$$

where  $\bar{\pi}$  is the basic profit flow, which is constant over time due to the fact that  $A$  and  $L$  in final goods production are constant:

$$\bar{\pi} = \left( \frac{1-\alpha}{\alpha} \right) A^{\frac{1}{1-\alpha}} \alpha^{\frac{2}{1-\alpha}} L \quad (21)$$

Due to the higher demand for goods of a higher quality level, as can be seen in the demand function (3), the profits of inventors  $\pi(\kappa_j)$  increase with the quality level  $\kappa_j$  of the variety of an intermediate good.

The incumbent monopolist can reap the monopoly profit  $\pi(\kappa_j)$  in every period until it is displaced by an intermediate goods firm inventing an even higher quality. The current probability, that the monopolist with a good of quality  $\kappa_j$  remains in the market, is therefore given by  $1 - p(\kappa_j)$ . Additionally, future profits are discounted by the current interest rate  $r$ . As intermediate goods firms assume that both the interest rate and the probability of a research success remain constant over time, the expected profit of a monopolist is given by:

$$\left( \frac{1 - p(\kappa_j)}{1 + r} \right) \bar{\pi} q^{\frac{\kappa_j \alpha}{1-\alpha}} + \left( \frac{1 - p(\kappa_j)}{1 + r} \right)^2 \bar{\pi} q^{\frac{\kappa_j \alpha}{1-\alpha}} + \dots + \left( \frac{1 - p(\kappa_j)}{1 + r} \right)^n \bar{\pi} q^{\frac{\kappa_j \alpha}{1-\alpha}} \quad (22)$$

Since this is a geometric series, by taking the limit  $n \rightarrow \infty$  this simplifies to:

$$E[V(\kappa_j)] = \frac{(1 - p(\kappa_j))}{r + p(\kappa_j)} \bar{\pi} q^{\frac{\kappa_j \alpha}{1-\alpha}} \quad (23)$$

---

<sup>11</sup>Therefore they implicitly assume that no new GPT arrives over the whole lifetime of their products, i.e. that  $a(t)$  is always 0.

In light of the above expression, the present value of profits of incumbents is decreasing in the probability of research success,  $p(\kappa_j)$ , for innovators who seek to improve the level of quality to  $\kappa_j + 1$ . As due to the Arrow replacement effect, incumbents do not engage in R&D since this would undermine their own monopoly duration time, a larger  $p(\kappa_j)$  increases the likelihood that an innovator succeeds and replaces the monopolist, i.e. monopoly duration time is declining in  $p(\kappa_j)$  which reduces the present value of profits. Moreover, the expected profit from a successful innovation rises with its quality level, due to the higher demand for higher quality intermediate goods. Contrarily, both a higher discount rate and a higher probability of being displaced by a future competitor lower the expected profit.

### 2.3 Model Equilibrium

Assuming free entry in the intermediate goods sector we can now find the optimal amount of R&D expenditures  $Z(\kappa_j)$ , by equalizing expected payoff of such an investment with the according probability of having a research success  $p(\kappa_j)$  multiplied by the expected monopoly profit associated with inventing an intermediate good of higher quality,  $E[V(\kappa_{j+1})]*p(\kappa_j)$ . Therefore the free entry condition is given by:

$$Z(\kappa_j)(\phi(\kappa_j)B(t)E[V(\kappa_{j+1})] - 1) = 0 \quad (24)$$

In order to find the equilibrium aggregate research expenditures we can now insert the expected profit from having a research success given by equation (23) together with the difficulty of performing R&D (10) into this free entry condition. This allows us to easily solve for the probability of having a research success, which is given by:

$$p = \frac{\bar{\pi}B_m - r\zeta}{\zeta + \bar{\pi}B_m} \quad (25)$$

As this equation is independent of the quality level in a single sector, research expenditures are uniformly distributed among all intermediate goods sectors. By inserting this equation into the probability of having a research success as given by equation (9) we can derive the R&D expenditures in a single sector  $j$  and then aggregate across all intermediate goods sectors. This results in the following amount of aggregate R&D expenditures:



$$Z(t) = \sum_{j=1}^N Z(\kappa_j, t) = \frac{\bar{\pi} - r\zeta/B_m}{1 + B_m\bar{\pi}/\zeta} q^{\frac{\alpha}{1-\alpha}} Q \quad (26)$$

Since  $Y(t)$  is a linear function in the aggregate quality index  $Q$ , output growth is determined by the growth rate of  $Q$ . Given the leading edge quality  $\kappa_j$ , the probability of research success  $p(\kappa_j, t)$  determines the level  $Q$  in the next period

$$Q(t+1) = p(\kappa_j, t) \sum_{j=1}^N q^{\frac{(\kappa_j+1)\alpha}{1-\alpha}} + (1 - p(\kappa_j, t)) \sum_{j=1}^N q^{\frac{\kappa_j\alpha}{1-\alpha}} \quad (27)$$

$$= p(\kappa_j, t) q^{\frac{\alpha}{1-\alpha}} Q(t) + (1 - p(\kappa_j, t)) Q(t), \quad (28)$$

such that the growth rate of GDP reads

$$\gamma = \frac{Q(t+1)}{Q(t)} - 1 = (q^{\frac{\alpha}{1-\alpha}} - 1)p(\kappa_j, t) = (q^{\frac{\alpha}{1-\alpha}} - 1) \frac{\bar{\pi}B_m - r\zeta}{\zeta + \bar{\pi}B_m} \quad (29)$$

The growth rate of output,  $\gamma$ , depends linearly on the probability of research success,  $p(\kappa_j)$ . On one hand a higher  $p(\kappa_j)$  reduces the present value of incumbents but increases the speed of quality improvements since the probability of success per unit of resources allocated to R&D has increased. The probability of research success depends, in turn, positively on the level of the GPT<sup>12</sup>. Thus, the growth rate of output is positively associated to the level of the GPT. This means that the drop in the level of a new arriving GPT reduces output growth through the induced reduction in the probability of research success. The economy moves along a balanced growth path, if the the level of the GPT is constant. Then  $Y, X$  and  $Z$  are linear functions in  $Q$ . As moreover the households' problem is solved for by the optimal allocation of income to R&D, i.e.  $Z(t)$ , we know that  $Y, X, Z$  and  $C$  grow at the same and constant growth rate as specified by (29). Long-term economic dynamics are driven by a sequence of GPTs, such that the economy moves along the BGP only as long as the level of the current GPT has reached its upper bound and the probability of research success is constant. Long-run growth is however driven by a sequence of GPTs while the arrival of which is stochastic, despite the fact that the probability of such an event is endogenous to the model. These long-term dynamics are described in the next section

---

<sup>12</sup>Note that  $\frac{\partial p}{\partial B_m} = \frac{\bar{\pi}\zeta(1+r)}{(\zeta + B_m\bar{\pi})^2} > 0$ .

### 3 Model Behavior and Numerical Simulations

In order to illustrate the dynamics of the economy we calibrate our model. We define one period as being equivalent to one year.<sup>13</sup> Moreover, we calibrate our model to cover the historical arrival of new GPTs over the past two centuries, i.e. the years from 1809 until 2008 AD. We thereby again refer to the list of GPTs by Lipsey at all shown in Table 1. According to their list in the 19th century four GPTs appeared (in the order of their appearance: railway; iron steamship; internal combustion engine; electricity) while in the 20th century seven GPTs did arise (in the order of their appearance: motor vehicle; airplane; mass production, continuous process, factory; computer, lean production, internet, biotechnology). Therefore the targeted number of GPTs arriving during the 200 years covered by our simulation is taken as approximately 11, while the aimed growth rate in the final period of our simulation corresponds to the average growth rate of the OECD economy in 2008, which is at 2.9% (OECD, 2008). In addition, for OECD countries R&D expenditures as a share of GDP amounted to 2.3% in 2008 (OECD, 2011). In calibrating the model we proceed now in two steps. We first fix those parameters which are directly known. In a second step, we fix the remaining parameters in an iterative way in order to match the numerical results to the above described observations. To begin with, we normalize population size, the aggregate quality index,  $Q$ , and the lower bound of a GPT,  $\bar{B}$ , to 1, i.e.  $L = 1$ ,  $Q = 1$ , and  $\bar{B} = 1$ . The capital income share,  $\alpha$ , is fixed as usual to 0.3.<sup>14</sup> The world market interest rate,  $r$ , is set to 0.03 per year.  $A$  is a scale parameter which fixes  $\bar{\pi}$ , given  $\alpha$  and  $L$ . Therefore  $A$  steers the level of the probability of research success,  $p$ , and the growth rate of output together with  $q$  and  $\zeta$  and the level of the GPT. In order to match the afore mentioned values of output growth and the research expenditure share, we set  $A = 2$ ,  $\zeta = 2.4$ ,  $B^{max} = 6$  and  $q = 1.08$ . This implies an initial growth rate of output in the vicinity of 0.05% (see Galor and Weil, 2000) and a long-run growth rate between 2 and 3%. The implied probability of research success is then initially blow 10%. The remaining parameters trigger the dynamic behavior in terms of the increase in the growth rate of output and the number of GPTs developed over the past 200 years. We set  $\delta = 0.05$ ,  $\tilde{k} = 0.1$ ,  $k = 4$ , and  $\varphi = 0.0045$ . This generates a development pattern which is consistent to the observations over the last 200 years. In the 19th century the growth rate increased to about 1% per year and increased towards its current interval after World War II (see Galor and Weil 2011). In addition there arrived only 4 GPTs in the 19th century but 7 in the 20th century. To do so we have chosen the values so that in the average of one thousand simulation runs, the

<sup>13</sup>Simulations are also used by van Zon et al. (2003 and 2006) and Carlaw and Lipsey (2006) to show the long-term economic development driven by a sequence of GPTs. Unlike these models, our framework can account for the observed increase in the frequency at which new GPTs arrive. Carlaw and Lipsey (2006) calibrated their model to an constant expected time interval of 30 years between GPTs, while Van Zon et al. (2003 and 2006) make simulations taking arbitrary parameter values.

<sup>14</sup>The labor income share is  $1 - \alpha$  and amounts to 2/3, see Acemoglu (2009).

desired growth rate and arrival rate of GPTs is achieved.<sup>15</sup>

$\alpha$	0.3
$A$	2
$L$	1
$r$	0.03
$\zeta$	2.4
$\delta$	0.05
$B$	1
$B^{max}$	6
$\tilde{k}$	0.1
$k$	4
$Q(1)$	1
$q$	1.08
$\varphi$	0.0045

Table 2: Parameters used for numerical solution

The number of GPT generations arriving over the 200 years resulting from a total of 1000 simulation runs, are shown in Figure 1. The thin lines show the results of individual simulation runs, while the bold line represents the average vintage of GPTs present taken over all simulations. It becomes obvious that our model can be calibrated in a way that can realistically depict both the absolute number of GPTs invented in the past 200 years and their approximate arrival rate. The acceleration of the arrival of new GPTs is also mirrored by our model. Interestingly, while we can chose the parameters so that in terms of expected values, the historical development of the various GPTs can be approximated, there is a wide spread of other scenarios arising using the very same values. The number of GPTs invented during the time frame of our simulation ranges from 4 to 24. This clearly shows that, given that long-term growth is driven by the arrival of subsequent GPTs, the outcome is still highly stochastic.

The dynamics of our economy triggered by the repeated arrival of new GPTs is shown in Figures 2 and 3 for a typical simulation run.

As statet at the beginning of this section, our framework is able to capture important empirical regularities of economic development. Figure 2 is consistent with the arrival pattern of GPTs over the last 200 years and clearly consistent with the observed acceleration in the arrival of new GPTs. In addition the model is consistent with a slow take-off, that is the growth rate of aggregate output is increasing in accordance to the observed empirical pattern while the level of output follows an exponential trend. In line with our theoretical considerations, the growth rate of aggregate output follows the evolution of the probability of research success. The latter is triggered by the level of the GPT which in turn depends on the amount of acquired technological knowledge as

---

<sup>15</sup>This approach is also widely used in the simulation of business cycle models, as for example in Jaimovich and Rebelo (2006).

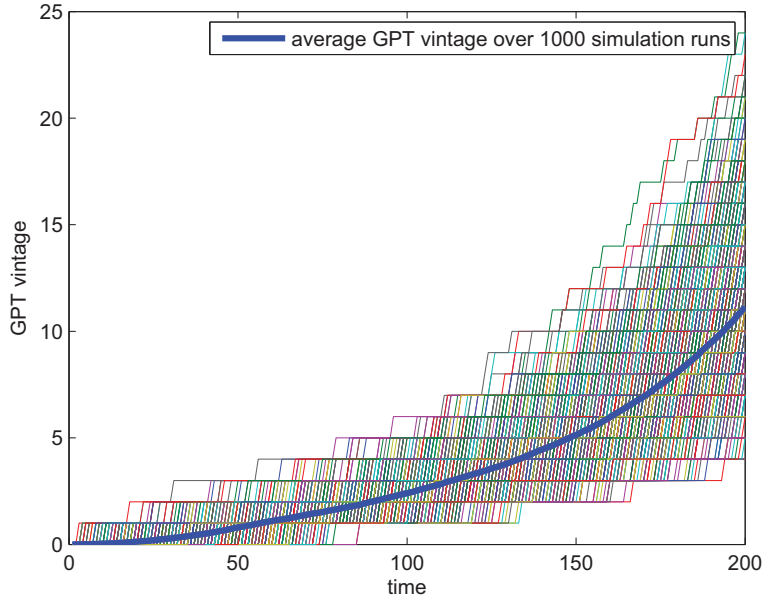


Figure 1: GPT vintage in the 1000 simulation runs

reflected by the number of quality improvements. Initially this experience is nearly inexistent and therefore the level of the GPT is also low which induces low probabilities of research success and low rates of growth.<sup>16</sup> It takes more than 40 years until the next GPT arrives. Since there is more applied knowledge available than 40 years ago, the initial level of this GPT is higher than the old one, such that  $p(\kappa_j)$  and the growth rate increase. Therefore the level of GDP and research expenditures speed up. Nevertheless, the growth rate is still quite low which means that the number of quality improvements (acquisition of applied knowledge) is also quite low. Therefore, the level of the GPTs evolves with a very low growth rate. There will be a point in time where the level of applied knowledge is sufficiently high, such that the level of the current GPT evolves at a higher pace. This speeds up growth and the number of quality improvements which makes the arrival of the next GPT more likely. Given that the economy reaches a stage of development with faster quality improvements, the introduction of a new GPT induces a structural break in the sense that the initial level of the new GPT drops compared to the previous level. This induces slow downs in economic growth. But given a high amount of applied knowledge with previous technologies, the diffusion of the new technology reflected by the number of quality improvements subject to this vintage speeds up such that the level of the new GPT increases again. Thus the last part of the development process is characterized by growth cycles, but increasing growth rates and increasing probabilities of research success.<sup>17</sup> The development of R&D expen-

<sup>16</sup>Technically this feature is owed to the logistic functional form of  $B$ .

<sup>17</sup>Note that growth slow downs in earlier stages may also occur. That this does not occur

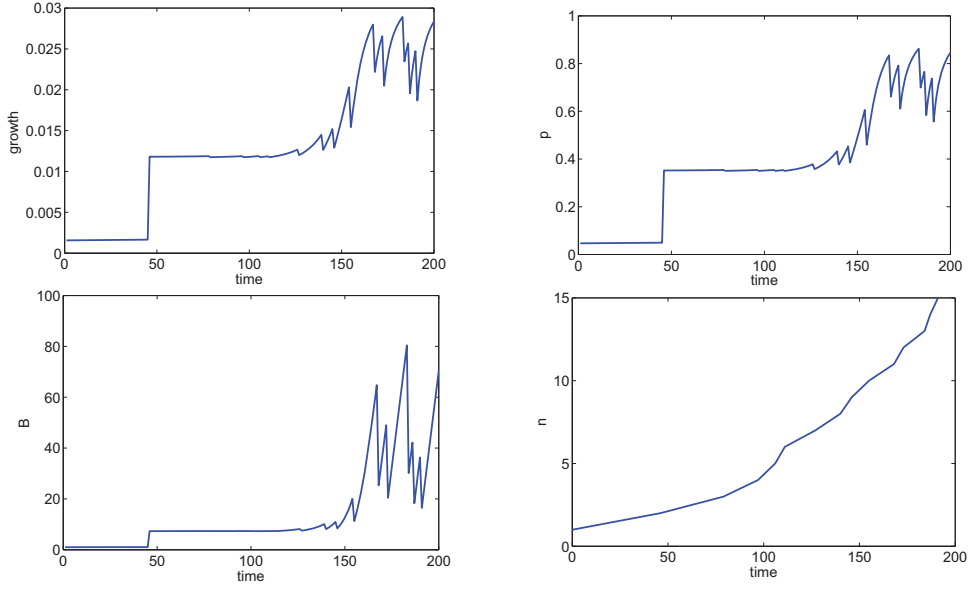


Figure 2: Typical simulation run: evolution of the growth rate of aggregate output,  $\gamma$ , the probability of research success,  $p(\kappa_j, t)$ , the level of a GPT,  $B(n, t)$ , and the sequence of the arrival of GPTs

ditures is equally interesting: Just as economic growth, R&D is subject to a cyclical behavior which is subject to the arrival of new GPTs. Furthermore an increase of R&D expenditures can be observed over time.

## 4 Concluding Remarks

We have presented a quality ladder model of endogenous Schumpeterian growth where new GPTs arrive endogenously with a probability governed by the amount of applied knowledge available. This model allows for a more realistic description of the historical facts surrounding the emergence of new GPTs and the frequency of their arrival which state that new GPTs arise in an ever higher frequency. Furthermore, not only the arrival of new GPTs is stochastic but also the development of new qualities of intermediate goods in single sectors is subject to uncertainty. This combination of features is both unique from a modelling perspective and fits stylized facts drawn from economic history, i.e. increasing growth rates. Thus, so far we presented a highly stylized framework which is able to replicate several features of economic development over the

---

in this simulation run is a result of the stochastic process. In any case, whether or not this occurs depends for a given shock on the level of  $\delta$  in relation to existing and new arriving technologies. More realistically it should be assumed that  $\delta$  varies with arriving technologies.

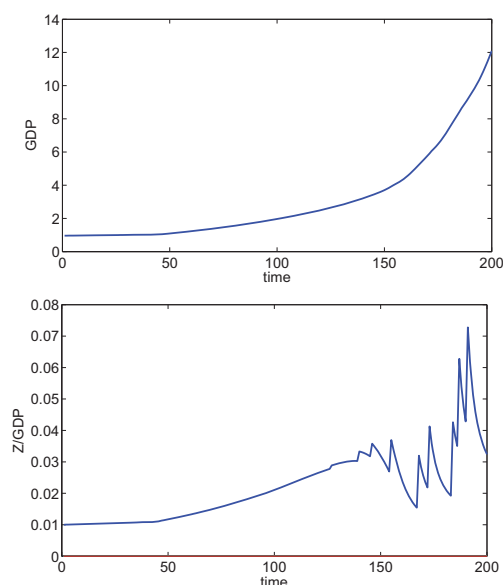


Figure 3: Typical simulation run: evolution of aggregate output,  $Y$ , and R&D expenditures as a share of GDP

past 200 years, i.e. decreasing time intervals between GPTs, the efficiency of a new GPT increases over time and GPTs are based on the existing stock of applied knowledge.

Nevertheless it is worth to notice, that in reality there exist more than one GPT at the same time. For example, Lipsey et. al (2005) distinguish five classes for GPTs: materials, information and communication technologies, power sources, transportation and equipment, and organizational forms. In this context, Carlaw and Lipsey (2011) observe that over time, many different GPTs within each class are invented and were in simultaneous use, for example electricity, water wheels and steam engines as power sources. Moreover, different GPTs may complement each other, like electricity enabled computers. Thus the adoption of a new GPT does not only depend on applied knowledge but also on applied GPTs. Other GPTs in turn have displaced some GPTs (for example the three masted sailing ship). Thus the life cycle of GPTs and their interaction with existing technologies is very uncertain in reality. We were already commenting on the assumption of a constant degree of complementarity between existing applied knowledge and a new GPT as captured by  $\delta$  in our framework. It seems plausible that the degree of complementarity interacts with the newly arriving GPT. Moreover, a GPT may be more productive in some sectors but not in others which again raises the question of heterogeneous GPTs. Thus a future model could consider that an ever increasing number of GPTs arriving could compete for scarce R&D resources, thereby partially obliterating the beneficial

effects of these “engines of growth”.

## References

Acemoglu, D. (2009): “Introduction to Modern Economic Growth”, Princeton University Press.

Aghion, P. and P. Howitt (1998a): “On the Macroeconomic Effects of Major Technological Change”, in: Helpman, E. (ed.), *General Purpose Technologies and Economic Growth*, Cambridge: MIT Press.

Aghion, P. and P. Howitt (1998b): *Endogenous Growth Theory*, Cambridge and London: MIT Press.

Basu, S., J.G. Fernald and M.S. Kimball (2006): “Are Technology Improvements Contractionary?”, *American Economic Review*, 96(5), pp. 1418-1448.

Bresnahan, T.F. and M. Trajtenberg (1995): “General purpose technologies ‘Engines of growth’?”, *Journal of Econometrics*, 65(1), pp. 83-108.

Carlaw, K.I. and R.G. Lipsey (2006): “GPT-Driven, Endogenous Growth” *The Economic Journal*, 116, pp. 155-174.

Carlaw, K.I. and R.G. Lipsey (2011): “Sustained Endogenous Growth Driven by Structured and Evolving General Purpose Technologies” *Journal of Evolutionary Economics*, 21, pp. 563-593.

David, P.A. (1990): “The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox”, *American Economic Review*, 80(2), pp. 355-361.

Eriksson, C. and T. Lindh (2000): “Growth cycles with technology shifts and externalities”, *Economic Modelling*, 17(1), pp. 139-170.

Galor, O. and D.N. Weil (2000): “Population, technology, and Growth. From Malthusian Stagnation to the Demographic Transition and Beyond”, *American Economic Review*, 90(4), pp. 806-828.

Helpman, E., ed. (1998): *General Purpose Technologies and Economic Growth*, Cambridge, MA: MIT Press.

Helpman, E. and M. Trajtenberg (1998a): “A Time to Sow and a Time to Reap”, in: Helpman, E. (ed.), *General Purpose Technologies and Economic Growth*, Cambridge: MIT Press.

Helpman, E. and M. Trajtenberg (1998b): “Diffusion of General Purpose Technologies”, in: Helpman, E. (ed.), *General Purpose Technologies and Economic Growth*, Cambridge: MIT Press.

Jacobs, B. and R. Nahuis (2002): “A general purpose technology explains the Solow paradox and wage inequality”, *Economics Letters*, 74(2), pp. 243-250.

Jaimovich, N. and S. Rebelo (2006): “Can new about the future drive the business cycle?”, *NBER Working Paper Series*, 12537.

Lipsey, R.G., K.I. Carlaw and C. Bekar (1998): “What Requires Explanation”, in: Helpman, E. (ed.), *General Purpose Technologies and Economic Growth*, Cambridge: MIT Press.

Lipsey, R.G., K.I. Carlaw and C.T. Bekar (2005): *Economic Transformations*, Oxford: Oxford University Press.

OECD (2008): *OECD Factbook 2006: Economic, Environmental and Social Statistics*, Paris and Washington, D.C.: Organisation for Economic Cooperation and Development.

OECD (2011), Main Science and Technology Indicators, OECD Publishing.

Romer, P.M. (1990): “Endogenous Technological Change”, *Journal of Political Economy*, 98(5), Part 2, pp. S71-S102.

Schiess, D. and R. Wehrli (2008): “The Calm before the Storm? - Anticipating the Arrival of General Purpose Technologies”, CER-ETH Working Paper 08/81.

Scotchmer, S. (1991): “Standing on the Shoulders of Giants: Cumulative Research and the Patent Law”, *Journal of Economic Perspectives*, 5(1), pp. 29-41.

Van Zon, A., Fortune, E. and Kronenberg, T. (2003): “How to sow and reap as you go: a simple model of cyclical endogenous growth”, *MERIT-Infonomics Research Memorandum series*, 2003-026.

Van Zon, A. and Kronenberg, T. (2006): “Energy transitions and policy design in a GPT setting with cyclical growth through basic and applied R&D”, in: De



Miguel, C., X. Labandeira, and B. Manzano (eds.), *Economic Modelling of Climate Change and Energy Policies. New Horizons in Environmental Economics*, Cheltenham, U.K. and Northampton, Mass.: Elgar.

Wehrli, R. and G. Saxby (2008): “General Purpose Technologies and Endogenous Growth: Modelling Approaches and Conclusions”, ETH Zurich, mimeo.