Supply Stocktake (1/10)

Note title: **Innovation as the engine of growth: A brief review of the academic literature for Central Bankers**

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A brief review of the academic literature for Central Bankers

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1. Monetary policy and long run growth

Why should Central Bankers be concerned with long run growth? It seems uncontroversial in the business cycle literature that monetary policy can have no lasting consequences on GDP growth: suddenly increasing the quantity of money will stimulate a higher level of real economic activity in the short run, but money is bound to remain 'neutral' in the long run, when monetary shocks are completely dichotomized from real variables.[1]

Money neutrality, however, does no longer hold in an endogenous growth framework (Aghion and Howitt, 1998). Once technological knowledge is introduced in a model of sustained growth, the neutrality of money ceases to be valid, provided innovation is generated endogenously as the result of economic agents' competitive behaviour. The monetary stimulus that produces a higher level of real economic activity in the short run is likely to result in a burst of technological innovation that would not otherwise have occurred.

Higher technological growth could be the result of a more rapid 'learning by doing' due to the increased economic activity, or the outcome of increased Research and Development (R&D) by companies to take advantage of temporarily enhanced profit opportunities.[2] In either case, even after prices and expectations have fully adjusted to the monetary shock, the level of real income will be permanently higher and the price level will have increased less than in proportion to the money stock.

By embedding temporary shocks into the economy's long run growth path, the endogenous growth approach therefore calls into question the traditional division of macroeconomic theory between trend and cycles. A positive money supply shock with real temporary effects – increasing output and employment today – will also increase the level of knowledge tomorrow. And knowledge, according to the large body of economic literature discussed in the rest of this note, will spur technological innovation and drive long run growth.[3]

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[1] Money is 'neutral' in the sense that changes in the level of nominal money have no effect on the real equilibrium. Money is said to be 'super-neutral' if changes in money growth have no effect on the real equilibrium.

[2] During economic expansions R&D investment can either become more profitable or can be more easily financed through retained earnings by otherwise cash-constrained firms.

[3] This is due to the 'spillover' effect of R&D discussed later on. Of course if agents started anticipating these spillover effects, Central Banks could not rely on this mechanism forever.

This note was produced as part of SEAD's long run growth programme, which aims at building a framework and toolkit for thinking about the drivers of economic growth and its prospects beyond the MPC's economic forecast horizon.

The note is organised as follows: section 2 discusses the main drivers of growth, sections 3 and 4 discuss the exogenous and endogenous growth models respectively, section 5 links the literature on endogenous growth to the business cycle and section 6 presents the rich empirical evidence on the impact of research and innovation on productivity growth.

2. The drivers of productivity growth: proximate vs fundamental causes

Since the work of Solow (1956) economists have attempted to understand the process of sustained economic growth and to account for large cross-country differences in output per-capita. Much of the divergence among countries took place during the nineteenth and early twentieth centuries, while post-war growth rates can only partly explain these differences.

Small differences in growth rates can have large impact on the level of per-capita output over time, and it is therefore important to understand which specific country characteristics have a *causal* effect on growth, including their policies and institutions.

Economists have been quite successful in identifying factors that *correlate* with post-war economic growth: namely, investment in physical and human capital (education). They also stressed the importance of understanding why economies differ in the *efficiency* with which they use their physical and human capital. The shorthand expression 'technology' is used to capture factors other than physical and human capital that affect economic growth and performance: variations in technology across countries thus include differences in production techniques, in the quality of machines used in production and in productive efficiency.

The analysis of long run GDP growth and its correlated factors is generally framed in terms of a production function F which relates the amount of inputs labour (or human capital) L and physical capital K to final output Y [4]

$$Y = AF(L, K) \tag{1}$$

The shift parameter A is interpreted as technological progress. The rest of this note presents a non-technical discussion of the ideas behind the theory of technological progress as the fundamental driver of growth. For this purpose, it focuses on those models of economic growth in which the role of technological progress is predominant.[5] Even in its narrow focus, this survey is not intended to be exhaustive, while it includes more in-depth

[4] Inputs will also in general include materials M. If M is omitted, Y needs to be interpreted as value added, i.e. output net of materials.
[5] Acemoglu (2009) and Aghion and Howitt (2009) provide recent surveys of the broader economic growth literature.

discussion of topics such as technology waves and the empirical evidence, which seem relevant to the current UK economic outlook.[6]

The correlates of economic growth, such as physical capital, human capital and technology are *proximate* causes of economic growth, i.e. they do not necessarily *cause* economic growth. There are reasons why technology, physical capital and human capital differ across countries. Acemoglu (2009) refers to these reasons are the *fundamental* causes of economic growth and groups them into four categories: luck, geography, culture and institutions.[7] Fundamental causes will have an impact on economic growth if they have a first-order influence on physical and human capital and technology.

3. Exogenous growth models

This note discusses economic models in which growth is only possible through technological improvements, where, as mentioned earlier, technology does not only mean advances in techniques of production and in knowledge, but also the general efficiency of the organization of production. The discussion begins with models of exogenous growth, in which technology is generated outside the model and taken as given. The most important of these are the Solow-Swann model and the neoclassical or Ramsey-Cass-Koopmans model.

3.1 The Solow-Swann model

The original contribution by Solow (1956) and Swann (1956) provide a tractable framework for studying the implications of capital accumulation and technological progress on GDP growth.

The Solow-Swann model is a general equilibrium dynamic model comprised of consumers and a representative firm. Consumers supply labour inelastically, in fixed amount L, and save a constant fraction s of their income. Firms produce final goods using physical capital K and labour L. Physical capital accumulation is driven by the saving rate s, which is taken as given in the model. The production technology, defined equation 1, expresses how much output can be produced given the available inputs, the capital stock and labour (K and L), under a given state of technological knowledge A.

The production function exhibits diminishing returns in its inputs K and L, which would eventually cause economic growth to cease, unless it is continually offset by technological progress. Technological improvements will increase production efficiency at a given level of inputs.

[6] This survey focuses on macroeconomic models of growth, therefore a notable omission is the vast Industrial Organisation literature which underpins the Schumpeterian models of section 4.2 (see e.g. Tirole, 1988).
[7] Luck: heterogeneity among countries leading to different selection among multiple possible equilibria with vastly different outcomes. Geography: soil quality, natural resources, climate, topography, and disease environment.
Culture: beliefs, values and preferences that influence individual economic behaviour such as occupational choice and the decision to invest in human capital. Institutions: rules, regulations, laws and policies that affect economic decisions such as investment in physical and human capital and technology.

The Solow-Swann model is important because it emphasises the notion that, in order to understand growth, it is important to understand physical capital accumulation and technological progress. These are however treated as black boxes in the model, since physical capital accumulation depends on the exogenous saving rate and technological progress is assumed to grow at a fixed rate.

3.2 The Ramsey-Cass-Koopmans neoclassical growth model

The neoclassical growth model, originated by a seminal contribution by Ramsey (1929) and elaborated by Cass (1965) and Koopmans (1965), differs from the Solow-Swann model in only one crucial aspect: it explicitly models consumer behaviour. The major contribution of the neoclassical growth model is to open the black box of savings and capital accumulation, by specifying households' preferences, and by linking them to the saving rate. Investment in physical capital, determined by the saving rate, is therefore determined endogenously and driven by the inter-temporal decisions of household, which are based on their preferences for consumption and leisure. The equilibrium growth rate of the economy in these models, however, is still derived exogenously, and is equal to the rate of technological progress.

Numerous extensions of the Solow-Swann and neoclassical model have been proposed: an important example is Mankiw *et al.* (1992) who extend the Solow-Swann model to include human as well as physical capital and find that differences in human capital investment across countries are important in explaining differences in output per capita.

The most important message of the exogenous growth literature is that, without technological change, growth will be eventually chocked off by the dimishing marginal product of capital. With technological change, however, growth can be sustained, and the economy will reach a steady state in which the rate of economic growth is equal to the rate of advance of technological progress.

The main limitation of the exogenous growth literature is that it provides no account of technological progress, which it takes as given by some unspecified process that generates scientific discovery and technological diffusion. The main problem with the assumption of exogenous technological change is that there are many reasons to believe that technological progress depends on economic decisions in the same way that capital accumulation does. In practice, new technologies are created by profit-seeking individuals and firms through research, development and incremental improvements, and innovation is usually the result of a process of market competition.

As the empirical evidence discussed in section 6 below shows, technological progress is likely to be a major factor in cross-country differences in prosperity. A better understanding of the drivers of technological progress is therefore essential in the study of economic growth.

4. Models of endogenous growth

By allowing technology to be generated within the model, endogenous growth theory provides a more satisfactory framework for the study of sustained growth and its

fundamental causes. In these models, technological progress occurs as a result of firms' investment decisions, which respond to incentives, market structure and policies.

In most of these models, innovation is the outcome of firms' investment in research and development. This is not the case, however, in Romer (1986), one of the first examples of a model featuring endogenous technological change. Romer's model treats *knowledge* accumulation as the by-product of *capital* accumulation, though technological *spillovers* across firms. Greater investment in physical capital increases the experience of workers and managers in the production process, making it more productive. Technology in the economy – summarised by A in equation (1) – evolves endogenously as a result of the investment decision of firms. Consequently, the growth rate of the economy is endogenous, even though none of the firms purposefully invest in research or new technologies.

Romer's description captures an important dimension of knowledge, namely that it is a largely *non-rival* good, i.e. once a particular technology has been discovered, many firms can make use of it without preventing others from using the same knowledge.

Following Romer's pioneering article, the endogenous growth literature has developed along three main strands, discussed in the rest of this section: the 'expanding variety' models, the Schumpeterian models and the models of directed technical change.

4.1 'Expanding variety' models

The innovations generated by the stock of knowledge are likely to increase companies' productivity growth via two main channels:

(i) *Process innovation*: the introduction of new productive processes increases the efficiency of production, reduces production costs and thus increases their productivity *directly*.
(ii) *Product innovation*: the creation of new products with higher value for the same amount of resources used causes an outward shift in the firm's demand curve: this will lead to higher revenues, thus increasing their productivity *indirectly*.

Romer (1990) introduced a model in which investment in R&D expands the variety of inputs or machines used in production by firms producing final goods. In this model, firms producing intermediate goods consciously decide to invest in research, which leads to the creation of new varieties of machines. This greater variety of inputs increases the 'division of labour' in production, thus raising the productivity of final good firms. This dynamic can be viewed as a form of *process innovation*.

An alternative model, which focuses on *product innovation*, was proposed by Grossman and Helpman (1991). In this model, R&D leads to the invention of new final (consumption) products. Household preferences exhibit a 'love for variety' in the sense that consumers derive greater utility when they consume a greater *variety of products*. Thus innovation leads to higher demand for the (new) final products, increases firms' revenues and therefore their productivity.

Both models exhibit similar results in terms of equilibria and welfare properties. In particular, the equilibrium rate of output and consumption growth in these models is below its optimal level, due to an *externality in research*. Firms' own R&D spending increases the productivity of other companies' research (*research spillovers*). Companies disregard these positive externalities in their decisions on how much to invest in R&D, and as a result the equilibrium level of private R&D investment is lower than the social optimum.

The characteristic of these 'horizontal' models of machines or product development is to assume away obsolescence of old intermediate inputs or products, which is a critical component of technological progress. While the expansion of variety of machines used in production capture certain aspects of innovation, most process innovation in practice either increase the quality of an existing product or reduce the costs of production. Similarly, once a new product is brought to market, it tends to replace the previous existing models. Technological obsolescence is at the heart of the Schumpeterian models of growth discussed next.

4.2 Schumpeterian models of endogenous growth

In his original work, Schumpeter (1942) introduced the concept of 'creative destruction' to emphasise the fact that the same innovations that drive growth by creating new technology also make the existing technologies obsolete. In the first Schumpeterian models of growth introduced by Aghion and Howitt (1992), growth is generated by a random sequence of quality improving (or 'vertical') process innovations that result from uncertain research activities. At any point in time, only the cutting-edge machine of each type is in use: when a higher quality machine is invented, it will replace the previous vintage of the same machine.

In these models, growth results from innovations that raise the technology factor A by improving the *quality* of intermediate products. If research is successful, the innovation will create a new version of the intermediate product, which is more productive than the previous versions.

Research is costly and uncertain, and the probability of success depends on the amount invested in R&D. Innovations arrive with random frequency and can have different sizes. The successful entrepreneur will become the monopolistic producer of the new intermediate good for one period and will earn a profit as a result. In the long run, the economy's growth rate will depend on the frequency and size of innovation.

4.3 Models of directed technical change

The models discussed in sections 4.1 and 4.2 focus on a type of technology that is 'neutral' with respect to the two factors of production, capital and labour. In practice, technological change often benefits some factors of production and some agents in the economy more than others.

Models of directed technological change attempt to explain endogenously the direction and bias of new technologies that are developed and adopted. They were introduced in a series

of papers by Daron Acemoglu and various co-authors[8] and are useful to investigate a wide range of questions, including the sources of skill biased technological change, the distributional consequences of the introduction of new technologies and the impact of international trade on the direction of technological change.

These models show that, under fairly general conditions:

- An increase in the relative supply of a factor of production (for example skilled relative to unskilled labour) always induces technological change that is biased in favour of this factor ('weak equilibrium relative bias').
- Contrary to basic producer theory, relative factor demand curves can slope upwards. If the elasticity of substitution between factors is sufficiently high, an increase in the relative supply of a factor induces sufficiently strong technological change to make the relative price of the abundant factor increase and the (long run) relative demand curve upward sloping ('strong equilibrium relative bias').

5. From growth to cycles: General Purpose Technologies

Economic development is often shaped by accelerations and slowdowns in long run growth, swings sometimes referred to as 'Kondratieff cycles'. A common explanation for these is the existence of 'General Purpose Technologies' (GPTs): these are major technological breakthroughs that affect production and innovation in many sectors of the economy. They appear as successive technology waves, where each wave begins with a fundamental innovation and is followed by a sequence of incremental innovations.

The term GPT is usually reserved for changes that transform both household life and the ways in which firms conduct business, and therefore affect the whole economy. More specifically, a GPT will generally have the following three characteristics (Jovanovich and Rousseau, 2005):

a. *Pervasiveness:* it should be widely used and spread to most sectors.
b. *Improvement:* it should be capable of ongoing technical improvement and as a result should keep lowering the costs to its users.
c. *Innovation spawning:* it should make it easier to invent and produce new products or processes.

The steam engine, the electric dynamo, the laser and information and telecommunication technology (ICT) are often-cited examples of GPTs.[9]

Although each GPT raises output and productivity in the long run, it can also cause cyclical fluctuations. An aggregate productivity slowdown is often observed after the arrival of a new GPT, since its diffusion requires complementary inputs and learning, and might draw

[8] See Acemoglu (2009) for a summary.
[9] Jovanovich and Rousseau (2005) test the hypothesis that electrification and IT are both GPTs by measuring the three characteristics above. They conclude that, despite some important differences, the concept of GPT fits both technologies reasonably well.

resources from normal production activities. A new GPT requires costly restructuring and adjustments to take place, which might not necessarily take place smoothly over time.

A fruitful modelling approach based on the notion of GPT is that of the so-called 'Schumpeterian Waves' described in Helpman and Trajtenberg (1994). Their model assumes that a new GPT requires an entirely new set of intermediate goods before it can be implemented, whose development is costly. During the period between the discovery of a new GPT and its ultimate implementation, national income will fall, as resources are taken out of production and put into R&D activities aimed at the discovery of new intermediate inputs. Thus the initial effect of a positive technology shock may not be to raise output and productivity but to reduce them. Cyclical downturns may be the price needed to pay in order to implement the GPTs that delivers growth in the long run.

6. Empirical evidence on the impact of research and innovation on growth

Early empirical work on the sources of productivity growth revealed that growth in physical and human capital could explain less than half of such growth in the United States and many other countries.[10] The unexplained growth was ascribed to 'technical change' and a large literature originated that attempted to find a way to measure technical progress that reflected improvements in capital and labour quality or R&D activities, and which could explain the 'residual' or unexplained productivity growth.

6.1 The search for private and social returns to R&D

In the models introduced above, R&D can increase productivity by improving the quality of existing goods or reducing their average production costs or by increasing the number of final goods or intermediate inputs available. These improvements can lead to higher productivity via three main channels:

- *Within-firm* increases in productivity deriving from price reductions and profit increases.
- *Between-firm* increases in productivity deriving from factor and market share reallocations across firms.
- *Net market entry*: entry in the market of new, more productive firms or exit of incumbent, low-productivity firms.

Moreover, R&D carried out in one firm, sector or country may produce positive knowledge spillover effects to other firms, sectors or countries.

The empirical approach to measuring the rate of return to R&D assumes that technical change is the result R&D efforts and this is reflected in the technology factor *A*. This term,

[10] Differences in those factors cannot explain the large observed cross-country differences in income per capita either.

also named 'Total Factor Productivity' (TFP) is measured as the growth in output that is not accounted for by growth in the inputs labour and capital.

Assume the production function in (1) takes the Cobb-Douglas form:

$$Y = AL^{\alpha}K^{\beta}e^{u} \tag{2}$$

where u is a disturbance term. Let R be knowledge (intangible) capital that belongs to the firm and R^o be the external knowledge capital, that is the knowledge capital held by other firms in the sector or by other countries. Augmenting the production function in (2) with the knowledge capital terms gives:

$$Y = AL^{\alpha}K^{\beta}R^{\lambda}[R^{o}]^{\varphi}e^{u} \tag{3}$$

The coefficient λ measures the elasticity of output with respect to private (own) R&D capital while φ is the elasticity of output with respect to social (external) R&D capital (the *research spillove*r term). In empirical estimations, knowledge capital is often proxied by a measure of cumulated R&D or by R&D intensity.

Hall *et al.* (2010) summarise the vast empirical literature on the impact of R&D on productivity based on specifications of the (Cobb-Douglas) production function with R&D capital such as equation (3), estimated on firm-level, industry or country level data, either along the cross-sectional dimension or also exploiting the temporal dimension.

Although the studies are not fully comparable, on the whole Hall *et al.* conclude that rates of return to *own* R&D in developed economies during the past half century have been strongly positive, are likely to be in the 20% to 30% range.[11] Estimates of the own rate of return to R&D based on industry data are generally quite close to those obtained from firm data.[12]

In contrast, the estimated rates of return to *outside* R&D (the *research spillover* effect) are highly variable, ranging from 80% to statistically negligible. Moreover, these estimates are in general less precise than those for the own rate of return. This is partly due to the wide range of spillover measures used, which makes it difficult to compare across studies. Hall *et al.*, however, conclude that in most cases the estimates are significant and indicate the existence of major spillovers of research across industries or countries.

Overall, these studies have revealed the complexity of the estimation task, affected by issues such as omitted variables, measurement errors and adjustment costs, and a number of fairly complex econometric methods have been developed to deal with these problems. Despite these difficulties, it can be concluded that rates of return to both private and social R&D capital are positive in many countries, and usually higher than those to physical capital. Social returns are almost always estimated to be substantially greater than the private returns.

[11] Rates of return are estimated by the marginal (revenue) productivity of a given measure of innovation.
[12] For an example of study using UK firm level data, see Rogers (2010).

6.2 Broader innovation and productivity growth

For reasons of data availability, the empirical research on the impact of innovative activity on productivity in firms has mostly used R&D spending and patent counts as measures of innovation. As the industrial structure of advanced economies shifted away from manufacturing and towards services, economists have realised that concepts like 'technical change' and 'R&D' describe only some of the sources of increased productivity, and have begun to look at innovation more broadly as a source of growth. This research has been greatly helped by the introduction of the Oslo Manual (Tanaka et al. 2005) with guidelines for the definition of various kinds of innovation, and by the diffusion of surveys of innovative activity in business firms across a large number of countries around the world, mostly using this manual as a guide. An example is the Community Innovation Survey (CIS), a Europe-wide survey of firms' innovative activities, which includes the UK Innovation Survey (UKIS).[13]

Hall (2011) summarises the numerous studies that have attempted to estimate a quantitative relationship between firm-level productivity and innovation measures explicitly, most of which use data from the CIS or its imitators in other countries. Three measures of innovative activities have been studied: (1) the percentage of sales that can be attributed to the sales of innovative products (2) *product innovation*, defined as a binary measure equal to 1 if the firm introduced a "new or significantly improved product (good or service)" in the previous few years (3) *process innovation*, equal to 1 if the firm introduced a "new or significantly improved productive process" in the previous few years.

Hall concludes that measures of innovative sales like (1) are associated with higher productivity, and that the association is stronger for higher technology sectors, while the service sector and the low technology sectors have lower elasticities. For measures of product innovation such as (2), in manufacturing sectors in Western Europe, typical values are around 0.05-0.10, implying that product innovating firms have an average productivity that is about 8 per cent higher than non-innovators, but there is a wide dispersion.

The impact of process innovation measures such as (3) is more variable, and often negative, possibly because the measurement error in the process innovation variable is severe enough to affect the results.

Only a handful of studies have focused on UK innovation data: Criscuolo and Haskel (2003) use the second and third waves of the UKIS to estimate the impact of product and process innovation on productivity; Griffith *et al.* (2006) compare results across four European countries, France, Germany, Spain and the UK (using the UKIS3); and recent Bank analysis) compares pre- and post- financial crisis innovation investment and performance.[14] These studies find that the impact of innovation on productivity among UK companies ranges between 0.05 and 0.20 for product innovation. Process innovation does not appear to have a significant impact on firms' productivity *levels*, but enters significantly positively in regressions of productivity *growth*.

[13] See https://www.gov.uk/government/collections/community-innovation-survey.
[14] In addition, Hall and Sena (2014) investigate the relationship between appropriability mechanisms (formal, such as patents, or informal, such as secrecy), innovation and firm level productivity.

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