NERI Working Paper Series

# Innovation and Growth: Concepts and Policy Implications

Thomas A. McDonnell

December 2018

NERI WP 2018/No 58

For more information on the NERI working paper series see: www.NERInstitute.net

**PLEASE NOTE: NERI working papers represent un-refereed work-in-progress. The author is solely responsible for the content and any views expressed therein. Comments to the author by e-mail are invited. The author grants permission to cite this paper.**

# Innovation and Growth:
# Concepts and Policy Implications*

**Thomas A. McDonnell**** (NERI) Nevin Economic Research Institute, Dublin, Ireland

**Keywords:** Innovation; Technological Change: Diffusion Processes; Institutions and Growth

**JEL Codes:** O30; O33; O43

---

**ABSTRACT**

This paper discusses the main concepts behind knowledge as an economic good and the production and diffusion of new ideas. Doing so is motivated by the understanding that knowledge and new ideas manifesting as 'innovations' are the key to sustainable long-run economic growth. The paper proceeds as follows. I begin by establishing technological change and new ideas as fundamental to sustainable long-run economic growth. Significantly, productivity led growth, unlike accumulation led growth, need not be harmful to the environment and is potentially sustainable ad infinitum. I next describe the main models of innovation and growth. These include the endogenous models, the evolutionary models and the neo Schumpeterian models. I next discuss the concept of a system of innovation, along with the concept's relevance for innovative capacity. Innovation production and diffusion are things that occur within an economic system made up of a multitude of individuals and organizations, each with their own abilities and incentives, and each operating under a particular set of rules and constraints. The paper presents a conceptual framework for understanding innovation systems and the processes of technology diffusion and adoption. Following the main discussion, I draw out a set of high-level implications to help guide policymakers.

**This version: 20 December 2018**

---

*This NERI Working Paper forms part of an NERI project on the related areas of growth, productivity, enterprise, industrial, and innovation policy in Northern Ireland and in the Republic of Ireland.

** The author gratefully acknowledges helpful feedback from a number of reviewers. The usual disclaimer applies. All correspondence to tom.mcdonnell@nerinstitute.net

# Innovation and Growth:
# Concepts and Policy Implications

**Thomas A. McDonnell** (NERI) Nevin Economic Research Institute, Dublin, Ireland

## 1 . INTRODUCTION

In this paper, I discuss the main concepts behind knowledge as an economic good. My doing so is motivated by the understanding that knowledge and new ideas manifesting as 'innovations' are the key to sustainable long-run economic growth. Following the main discussion, I draw out a set of high-level implications to help guide policymakers.

Economic growth can come from a number of sources. It can come from the accumulation of factor inputs, namely labour and capital. It can also come from productivity gains arising from technological progress and innovation, scale economies, or efficiency of factor use. However, the only sustainable form of growth is growth arising from productivity gains. Productivity gains come from the production, diffusion, and application of new knowledge and ideas within the economy itself.

The focus, in this paper is on the importance of innovation arising from the application of new and useful knowledge and ideas. We need to define what we mean by innovation. An innovation is a new idea, or combination of existing ideas that manifests as a new product or service, a new production process, a new market, a new source of supply, or even as a new organization. As it happens, the characteristics of knowledge mean that the market will, left to its own devices, invest less than the socially optimal amount in knowledge generating and diffusing activities. This implies a need for activist innovation policies while leaving open the question of what precisely those policies should be.

The quality and scale of innovation inputs is important. The classic image is of people in white coats working in a lab. However, we should not think of innovation as a linear process. Nor should we think of innovation as being about the invention of new cutting-edge technologies. Instead, we should think of innovation production and diffusion as something that occurs within an economic system. This system comprises a multitude of individuals and organizations, each with their own abilities and incentives, and each operating under a particular set of rules and constraints. Within most countries, technology diffusion is a much more significant driver of growth than new-to-the-world inventions. Fundamental to diffusion is communication. For this reason, the knowledge flows between individuals and organizations are crucial to the innovation process.

The government will always be the most significant actor within the innovation system. Governments have the power to set the 'rules of the game' and provide the incentives for market actors to engage in innovation activities. In this way, governments can counteract the structural market failure leading to the underproduction and slow diffusion of knowledge and innovation. Governments themselves provide much of the inputs to innovation in the form of spending on science and education, on Research and Development (R&D) and on knowledge infrastructure. Governments can also provide direct or indirect support to enhance the innovative capacity of enterprises.

The paper proceeds as follows. In the second section, we establish technological change and new ideas as fundamental to sustainable long-run economic growth. In the third section, we then describe the main models of innovation and growth. These include the endogenous models, the evolutionary models and the neo Schumpeterian models. The fourth section discusses the concept of a system of innovation, along with the concept's relevance for innovative capacity. In the fifth section, I move on to discussing the importance of technology diffusion and adoption, and sketch a framework for understanding these processes. The sixth section contains some policy recommendations and concludes.

## 2. NEW IDEAS AND GROWTH

A fundamental assumption of mainstream economic analysis is that economic growth is central to the task of improving overall living standards. There are of course caveats. An economic system that generates highly unequal growth may not benefit much of society, will be inefficient at reducing poverty, may erode social capital and trust, and may well be unstable over the long-run. Other forms of growth are also undesirable. For example, growth based on environmentally damaging practices is costly for current and future generations. Such costs may well outweigh the benefits, particularly in the long-term.

Environmentally damaging growth is also unsustainable on a finite planet. In the context of climate change, we can view growth based on investment in renewable energy infrastructure as desirable, whereas growth based on exploitation of carbon reserves as undesirable. A third example occurs where demand-side fiscal policies, such as tax cuts, are used for electoral or other reasons to temporarily accelerate growth at a time when the economy is already performing strongly, or are used to privilege sectoral interest groups. Such policies merely amplify the economic cycle, distort economic activity, and weaken the economy in the long-run.

Nevertheless, we can reframe the original assumption to account for these caveats. What we are interested in is *sustainable* and *inclusive* economic growth. Such growth is synonomous with most of the improvements in disposable income and living standards over the span of human history. By itself this claim is somewhat meaningless. After all, economic growth and income growth amount to essentially the same thing when considered at the level of the economy as a whole, although the distribution of that income will obviously affect well-being. So we need to dig a little deeper. Where does long-run economic growth itself come from?

Modern theories of long-run economic growth tend to strongly emphasise the importance of technological advance and its spread throughout the economy. Fundamental to this process of technological progress is the generation and diffusion of new knowledge (Aghion and Howitt, 2009). Knowledge is the key to unlock economic growth or "*Knowledge...is power*" to quote Francis Bacon's famous dictum (1597). Joel Mokyr (2002) describes the generation and application of new knowledge, or 'new ideas', as the wellspring or lever of riches that propels economies forward. So what do we mean by a new idea? We can think of a new idea as representing a new instruction or set of instructions for transforming economic inputs into outputs, or more evocatively, for transforming nature to better suit human needs (Mokyr, 1992).

### *2.1 New ideas*

What does a new idea represent if we consider it from an economist's perspective? A new idea is basically a new set of instructions about how to interpret or transform the world in some way. We can think of a technology, for example the combustion engine, as the outcome of a set of applied ideas or sets of instructions which have been developed and improved over time through an iterative evolutionary process. From this perspective, a subsequent improvement to the reliability, efficiency or applicability of our combustion engine can be understood as nothing more than an alteration to the set of instructions used to build or maintain the engine. Ideas and technologies will tend to successfully diffuse through the economy and society when they are economically advantageous compared to earlier ideas and technologies. We can think of this process as conceptually similar to that of evolutionary change within a population when a useful mutation spreads through that population.

### *2.2 Innovations*

We can use the term 'innovation' as a shorthand to describe knowledge based economic change. What is an innovation? Innovations are usually combinations of two or more existing ideas. Innovation can manifest as a new method or application, a new product or service, a new process, a new market, a new source of supply, or even a new organisation.

The potential for new ideas is effectively limitless. Paul Romer (1992, 1993) emphasizes the vast number of ways in which we can conduct any economic activity. He argues that technological change offers the prospect of continuous improvement in living standards. Romer describes each known combination of actions or instructions as a known technology. We can think of each alternative possible combination of actions as a potential innovation. He gives the example of sewing a shirt, an activity that requires fifty-two separate actions. Romer argues that even if most possible sequences of action are wildly impractical it is still *"extremely unlikely that any actual sequence that humans have used for sewing a shirt is the best possible one."* Romer's point is that the potential for continuous economic growth exists within the vast search space of untried combinations of actions.

### *2.3 Four characteristics of knowledge*

New ideas may lead to new opportunities or catalyse further new ideas. Indeed new ideas are almost invariably build on combinations of earlier ideas. Crucially, these new and useful ideas are themselves **non-rivalrous** in use (Table 2.1). This means that one person using a new idea, or new knowledge, need not prevent a second person from using that same idea. The non-rivalrous characteristic of knowledge differentiates it from other economic inputs into the production process such as land, buildings, machinery and labour. Knowledge does not exhibit diminishing returns. Instead it can generate economies of scale as the average cost of knowledge inputs decline with usage. Crucially, the non-rivalrous nature of knowledge enables positive spillover externalities in the economy.

Knowledge, once obtained, is virtually **inexhaustible**. We can use it repeatedly. The twin characteristics of non-rivalrousness and inexhaustibility generate increasing returns to scale. According to Arrow (1962, 1991), while the cost of acquiring knowledge is independent of the scale on which the knowledge is eventually used, the benefit obtained from the knowledge very much depends on the scale at which it is eventually used. Once we have created the knowledge, there is almost zero marginal cost involved with further use of the knowledge. In this way, new technology increases the marginal productivity of labour and capital. In other words, through continuous learning and the application of useful knowledge we can produce the same value of goods and services for increasingly less effort.

A third characteristic of knowledge is that it is only **partially excludable**. Once revealed, anyone can potentially use the new knowledge. In other words, the would-be producer of the knowledge will not necessarily be able to capture any or all of the benefits from its production. In the absence of some policy intervention, it may be difficult if not impossible for a firm to earn a profit from its knowledge production activities. As such, partial excludability creates a disincentive to engage in knowledge production.

Finally, the production of knowledge is a complex, interactive and uncertain process with no guarantee of an economic return. The inherent **uncertainty in the cost of production** is the fourth main characteristic of knowledge as an economic good. The consequence of this uncertainty, in combination with the inability of the producer to internalize all of the benefits of production, is that a self-regulating market will spend less than the socially optimal amount on knowledge generating activities. The resulting market failure provides a rationale for interventionist technology policy.

**Table 2.1 Characteristics of Knowledge**

| Characteristic | Description | Implication |
|---|---|---|
| **Non-rivalrous** | One person using the knowledge need not prevent a second person from doing so | Positive externalities in the form of technology spillovers |
| **Inexhaustible** | We again use knowledge repeatedly. Once obtained it has almost zero marginal cost | Increasing returns to scale |
| **Only partially excludable** | The knowledge 'producer' may not be able to fully internalize the economic benefits | Reduces market incentive to invest in knowledge production. Underproduction from a societal perspective |
| **Uncertainty in the cost of production** | The outcome of investment is unpredictable with no guarantee of any economic return | Reduces market incentive to invest in knowledge production. Underproduction from a societal perspective |

## *2.4 The cost of knowledge as the key to growth*

The core argument then is that new instructions applied for an economic purpose, which we simply call 'new ideas' or 'new technologies', are a fundamental part of the process of economic growth. In addition, knowledge based growth does not necessarily require the use of additional finite resources of land, labour and capital. It is instead based on enhancing the productivity of labour and capital inputs. Thus there is the potential for economic growth and development to effectively continue ad infinitum.[1] Crucially, technological change offers the possibility of decoupling growth from energy usage and therefore from climate change. In other words, productivity based growth need not be harmful to the environment and we therefore need not choose in the long-run between such growth and 'de-growth'.

If new ideas and technologies are indeed the *"fodder that fuels a nation's economic growth"* (Whitt, 2009, p.419), then it follows that we can influence the rate of growth by influencing the rate of production, development and diffusion (i.e. spread) of new ideas and technologies in the economy. One approach to achieving this goal is to find a way to reduce

[1] The academic literature calls this *intensive* growth. We can differentiate intensive growth from *extensive* growth. Extensive growth flows from the accumulation and use of resources, i.e. it is growth obtained from using more units of labour or capital, or both.

the cost of acquiring knowledge. An alternative approach is to try and increase the productivity of knowledge production and diffusion activities. A third approach is for policymakers to directly invest in knowledge production inputs. We will explore policy options in Section six.

Nathan Rosenberg (1972) and Romer (1990) argue that the key to influencing long-run economic growth is to first influence the cost of generating, diffusing and obtaining knowledge. More specifically, Rosenberg (1972) argues that the net cost of knowledge is the main determinant of the rate of innovation. Knowledge is obviously neither freely available nor omnipresent. Every innovation or incremental advance in the stock of knowledge has its own cost of production. Rosenberg suggests that the incentive for engaging in innovation activities will increase if the cost of producing or acquiring an innovation falls even without a commensurate decline in the benefits of the innovation. In a similar vein, Romer (1990) describes how '*influencing the cost of finding new ideas*' is the key to economic growth. The market and market players are not the only influences on the rate of innovation. The economy's institutional make-up and constraints will also matter to the extent that these institutions influence the costs and benefits of engaging in knowledge production and other innovative activities.

For illustrative purposes we can give one policy example at this stage. Certain technologies, such as broadband internet access, are significant because they provide fast, reliable, and low cost access to the World Wide Web. By doing so they reduce search costs for access to the stock of existing knowledge. These technologies also facilitate the transmission and diffusion of new ideas and technologies. This suggests that the provision of cheap and universal access to broadband is, all else equal, a growth enhancing policy. The production and diffusion of knowledge will increase because the relative price or cost of undertaking knowledge generating activities will have fallen.

## 3. MODELS OF INNOVATION AND GROWTH

There are a number of seminal overviews of the main theories purporting to explain the causes of economic growth (see for example Bart Verspagen, 2005; David Warsh, 2006; Daron Acemoglu, 2009; and Philippe Aghion and Peter Howitt, 2009). The most influential of the contemporary growth theories include the new growth theories; the evolutionary growth theories; the neo-Schumpeterian growth theories, as well as the various growth theories rooted in complex models of the economy.

### *3.1 Early models*

A number of economists in the early twentieth century recognised the position of technological progress as the primary engine of long-term economic growth, including Allyn Young (1928) and Joseph Schumpeter (1942). However, technological progress was of secondary status in the orthodox growth models of the period. These models treated growth in the capital stock and the size of the labour force as the main causes of growth. Higher levels of investment would lead to faster capital accumulation and factor accumulation would increase per capita output. William Easterly and Ross Levine (2001, p.2) note that the emphasis on factor accumulation has persisted in the economic growth literature, for example they point to Debraj Ray (1998) as referring to investment and savings as "the foundations of all models of economic growth".

Growth theories began to focus on technological change and innovation from the 1950s onwards. The neoclassical growth models of Robert Solow (1956, 1957) and Trevor Swan (1957) explained how the long-run per capita level of output produced in the economy would be static unless the productivity of capital and/or labour grew over time. Diminishing returns to capital and labour would make it impossible to sustain economic growth in the absence of such productivity improvements. In these models, per capita output had a long-run constraint that depended on the savings rate. As the capital stock increased so too would total capital depreciation. Eventually, annual capital stock depreciation would become so large it would completely cancel out the annual additions to the capital stock at a given savings rate.

Sustained long-term growth was only possible if there was technological progress. Moses Abramovitz (1956) and Solow (1957) used growth accounting methods to separately estimate that fully 85 to 90 per cent of economic growth in the US economy over the previous century could not be explained by the increases in the capital stock and labour force over the period. Attention focussed on the source of the unexplained or 'residual' growth. Solow and Swan both assumed that higher productivity arising from technological progress was the reason for the residual growth. They posed the question of how and why this technological progress came about. While the Solow-Swan models incorporated the effects of technological change within the unexplained residual, there was an assumption that technological change was exogenous to the economic system. We now call the unexplained residual Total Factor Productivity (TFP).

TFP represents growth in the productivity of capital and labour, though as Easterly and Levine (2001) point out, TFP includes not just changes in technology, but other factors such as changing policies and institutions. Abramovitz (1956) also argued that the residual included a number of elements besides technological progress. He described the residual as a measure of our ignorance about how the economy changes over time. A key shortcoming of the basic Solow-Swan growth model was that the long-run per capita growth rate was entirely determined by an element outside or 'exogenous' to the model (Snowdon and Vane, 2005). While the basic neoclassical growth models did not explicitly seek to explain the causes of technological change, they are important because they pointed to the role of technological change in determining long-run standards of living.

Nicholas Kaldor (1957) made technological change endogenous to his growth model by introducing a 'technical progress function'. The Kaldor model emphasizes the role of positive endogenous feedback loops between economic growth and knowledge generation. Kenneth Arrow (1962) subsequently developed an endogenous 'learning by doing' growth model, in which serendipitous learning generates technological progress as a by-product of economic activity. Arrow shows how the productivity of labour increases with experience while technological progress caused by learning raises the marginal productivity of capital. If large enough, such productivity increases could counteract the effect of diminishing marginal returns to capital and labour.

The learning by doing model was similar to the older exogenous neoclassical models with the exception that it did not assume diminishing returns to factor inputs. Arrow (1962, 1991) was able to show how the non-rivalrous nature and inexhaustibility of knowledge could generate the increasing returns to scale necessary to generate long-term increases in productivity. The early endogenous models represent important advances in understanding economic change because they were the first mainstream growth theories to offer explanations for why technological change occurred and for why it propelled economic growth.

### *3.2 Knowledge production as endogenous*

The 'new' or 'endogenous' growth theories were a response to a dissatisfaction with earlier exogenous models that left technological progress as an unexplained residual. The endogenous models emphasize a role for policymakers and, in particular, emphasize the importance of investments in technological change, in human capital and in the diffusion of innovation. The new growth models assume technological change occurs endogenously within the economic system (Barro and Sala-i-Martin, 1995) and that positive externalities arising from innovation have an important impact on long-run economic growth and development. These models view new ideas and technical change as being determined, or *induced*, by the purposive motivations and decisions of rational and optimising economic actors. As such, technical change is considered endogenous to economic activity.

The new growth models emerged in the 1980s. Their central proposition is that capital accumulation when taken in its broadest sense to include human capital does not exhibit diminishing returns (Mankiw, Romer and Weil, 1992). We cannot directly measure human capital although we can use skill levels and particularly educational achievement as proxies. The accumulation of human and physical capital together with the production of new knowledge created through Research and Development (R&D) activities drives the process of economic growth in these models (Snowdon and Vane, 2005). We can think of these models as input-output models of innovation. Higher levels of investment in innovation inputs, such as education and R&D, will translate into higher levels of innovation outputs and therefore faster levels of economic growth.

Paul Romer (1986, 1990) built on Arrow's learning-by-doing model by introducing an R&D sector to the economy. He was able to describe how at the aggregate level we can achieve increasing returns to scale through the spillover of technology. The non-rivalrous nature of knowledge goods meant that new ideas, once created, could be used over and over again at no additional cost to the firm (Romer, 1990), while learning externalities among firms caused by knowledge spillover could lead to an expansion of aggregate knowledge (Romer, 1986). As a firm cannot fully internalize the benefits of a firm's investment in knowledge, the investment in knowledge (R&D) by one firm generates a positive externality that increases the productivity of other firms and economic actors.

The implication is that the public benefits to R&D will exceed the private benefits. Charles Jones and John Williams (1998) find that the social, i.e. economy wide, rate of return to R&D is between two and four times the private rate of return to R&D. On the other hand, the inability of knowledge producers to internalize all of the benefits of their investments reduces the incentive to undertake such activity in the first place. In addition, while knowledge has a once off payment, the size of the payment is of unknown cost beforehand. This makes knowledge production inherently risky and further diminishes the private incentive to produce knowledge.

The new growth models therefore predict that, when left to its own devices, the market will produce less than the socially optimal amount of new knowledge. The resulting market failure in the production of knowledge is a standard rationale advanced in support of activist technology policy, whether in the form of R&D subsidies or tax breaks for the private sector or in the form of direct government investments in R&D, education, knowledge infrastructure, and supports for the diffusion of innovations.

However, it would be wrong to treat R&D and associated spending as linear inputs into the innovation process, or indeed the only inputs that matter. Knowledge production is inherently different to production of other goods and services. Production and diffusion occur within a system. Even so, McDonnell (2017) and McDonnell and Goldrick-Kelly (2018) show that the Republic of Ireland invests significantly less on R&D per capita and other innovation inputs than comparable high income Western European countries. This underinvestment is likely to dampen innovation based growth in the Republic over the long-term.

### *3.3 Knowledge production as evolutionary and path-dependent*

While the new growth models treat technological change as endogenously induced, the evolutionary or *path-dependent* models of economic growth emphasise that economic change actually occurs as part of a historically grounded and dynamic path-dependent process characterised by permanent disequilibrium (Nelson and Winter, 1982; Mokyr, 1992). Bart Verspagen (2004) contrasts the steady state or 'clockwork' growth pattern of the new growth theories with the more uncertain growth trajectories predicted by the evolutionary theories.

The evolutionary models stress that dynamic change happens over historical time with the rate and type of technological change occurring as part of a stochastic (i.e. semi-random) process characterized by uncertainty. New ideas, like genetic mutations, are not entirely random. All ideas emerge out of something else, and are almost always variants on ideas that already exist. The evolutionary models see innovation as blind, with its success or failure partially driven by economic processes and partially driven by luck and context (Metcalfe and Georgiou, 1997).

The uncertainty of outcome is a function of what Mokyr (1992) describes as the Darwinian nature of technological change. According to this view, we can treat markets as selecting, or adopting, innovations or 'novelties' within a constrained Darwinian process. Innovations occur stochastically within the economic system and the eventual success or failure of a particular innovation is unknown in advance. The novel idea underpinning the innovation is synonymous with a genetic mutation. The innovation's eventual success or otherwise will partially depend on luck and context, but will also depend on the innovation's own characteristics such as its usefulness, its applicability, its compatibility with existing technology and its relevance to perceived needs.

The evolutionary theories reject the endogenous growth models' assumption of rationally optimising individuals. Kurt Dopfer (2005) argues that no single organization or individual can perfectly foresee the path of economic change or the potential of an innovation. Far from possessing perfect rationality under all circumstances, we can see organizations and individuals as acting under conditions of *bounded rationality*. Bounded rationality means that economic actors are only partially rational with cognitive limitations and biases in their ability to formulate, process, and solve complex problems (Kahneman, 2003 and 2011). Consequently, individuals and organizations must learn and search experimentally in uncertain and permanently changing environments and with uncertain outcomes (Hanusch and Pyka, 2005). Uncertainty of outcome and even lack of basic awareness of potential outcomes will often prevent economic actors from engaging with or investing in innovation.

From a policy perspective, the evolutionary models provide rationales for governments to minimize the risks involved in innovative activities and to promote general awareness of the potential benefits of innovations. There are important roles for governments to play. These include A) creating an environment and set of incentives that encourages and facilitates the generation of economically useful new ideas or 'mutations', B) removing blockages or barriers to innovation, and C) supporting the transfer of knowledge and diffusion of new ideas at the individual, organizational and economic system levels.

### *3.4 Transformative technological change*

The neo Schumpeterian models (Grossman and Helpman, 1991; Aghion and Howitt, 1992) treat the transformative processes driving economic change as endogenous to the economic system. These processes are a function of knowledge production, innovation and entrepreneurship occurring at the micro level (Hanusch and Pyka, 2005). The neo Schumpeterian models retain many elements of the endogenous growth framework. However, they also incorporate the evolutionary perspective of technological change as an uncertain and path-dependent process, as well as an understanding of the economy as a complex system characterised by networks and feedback loops.

In the neo-Schumpeterian framework, Darwinian competition *between innovations*, rather than competition between firms, is the central force propelling economic growth. The economy enters a new phase of growth when a new and more efficient technology spreads throughout the economy. The new technology renders older products and services obsolete and over time raises the economy's productive potential. Jobs, businesses, and even industries better able to exploit the newer more efficient and useful technology will replace those that are unable or unwilling to adapt to the new reality.

This process of economic upheaval and change is seen as perpetual and a feature of the economic system. Economic change ebbs and flows along with what Joseph Schumpeter (1942) calls the *''creative gales of destruction."* Over time these newer innovations are themselves displaced by the next wave of innovations and the productive potential of the economy increases yet again as the economy fluctuates and remakes itself in turmoil. Under this framework, economic growth is sustainable ad infinitum provided the process of creative and destructive innovation is not impeded (Aghion and Howitt, 2009).

Philippe Aghion and Peter Howitt (2009) identify two main inputs to innovation:

a) The expenditures made by the public and private sectors to produce innovations, and
b) The publicly available stock of innovations already produced by past innovators.

Some innovations are more significant than other innovations. Certain transformative technologies or 'macro inventions' will generate periods of radical economic change. However, more extended periods of smoother economic development and incremental change will punctuate such periods of radical change. Timothy Bresnahan and Manuel Trajtenberg (1992) and Elhanan Helpman and Trajtenberg (1998) develop the concept of General Purpose Technologies (GPTs) to explain the periodic occurrence of radical economic change and leaps and bounds of innovation. GPTs are described as technologies possessing at least three particular characteristics:

1. High potential for improvement,
2. Pervasiveness in the economy, and
3. An ability to enhance connectivity and/or innovation potential within the economy.

Historical examples of such transformative GPTs include, but are not limited to, fire, steam power; the telegraph; electricity; the railroad; the microprocessor, and internet access technologies. All of these technologies lowered either transportation or communication costs and by so doing reduced the cost of accessing and discovering new knowledge.

The new and more densely connected economic system that follows in the wake of the diffusing GPT gains an enhanced capacity to absorb and exploit new ideas. Vernon Ruttan (2008) argues that GPTs encourage greater investment in R&D because they reduce the cost of knowledge and therefore increase the productivity of R&D investments. The introduction and subsequent development of a GPT potentially opens up a wave of new innovation possibilities. An important implication is that policymakers should aim to ensure the successful development and diffusion of these technologies.

## 4. A SYSTEM OF INNOVATION

We cannot reduce technological change to a simple input-output dynamic. Technological change is a complex phenomenon. Complexity models of economic growth are rooted in chaos theory. They emphasise that the economy is a complex adaptive system characterised by a multiplicity of interactions between economic actors and by a multiplicity of positive and negative feedback loops (Frenken, 2005 and 2006; Arthur, 2009). Such models approach economic analysis from a network or system perspective rather than from a production or utility function perspective. The complexity models see economic growth as an outcome of the exploitation of increasing returns from new and useful innovations. Innovation itself is treated as an ongoing iterative process characterised by positive feedback loops.

The complexity models are characterised by non-linear relationships and by emergent properties. Optimal outcomes are unlikely and new possibilities are continuously emerging as part of a dynamic process within the system. The human capacity to predict the behaviour of such complex systems is limited. Consequently, these models emphasise the difficulty in picking technological winners. Therefore rather than focusing on picking winners, policymakers should instead seek to nurture a diverse, dynamic and competitive marketplace of ideas, with its own internal processes of Darwinian selection. Culture, networks and institutions are important because they influence the spread and adoption of new ideas. One implication is that we can enhance innovative capacity by having an open society. The rate of innovation is a function of the prevailing socio-economic environment, including beliefs, types of knowledge flows, sets of incentives, and legal, political and cultural rules of the game.

As it happens, rates of technological change and adoption vary greatly across countries, regions, industries, firms, households and individuals. We want to understand what drives these differences in technological change and adoption. Technological change does not occur in a linear sequence, but through feedback loops within a system. The flows of technology and information among people, enterprises and institutions are crucial to learning and interaction, and therefore crucial to the innovative process (Pontikakis, McDonnell and Geoghegan, 2006).

The economic system's ability to generate original ideas and to communicate, diffuse and assimilate existing innovations is called its 'innovative capacity' (Furman, Porter and Stern, 2002). At a national level, we can think of it as National Innovative Capacity (NIC). Innovation is an interactive process and the 'innovation systems' concept was developed in the late 1980s and early 1990s to explain why economies and societies differ in their rate of knowledge production and in their rate of diffusion of innovation (Freeman, 1991;

Lundvall, 1992; Nelson, 1993; Edquist, 2004). The approach emphasizes the systemic nature of innovation processes. The economy's institutional structures are key to the innovation process to the extent that they condition the incentives, expectations, and behaviour of economic actors as well as the type and strength of knowledge flows.

According to David Jacobson (2013): *"the interacting institutions at the heart of a system of innovation include the educational, cultural, social and economic, as well as the policy and political factors that influence how creative, entrepreneurial and change-oriented people are, in the social formation of which the system of innovation is part." A* crucial part of the National System of Innovation (NSI) concept is the notion that innovation occurs within a complex system containing a multitude of economic actors, relationships between these actors, and a set of institutions establishing the rules of the economic game.

Economic history and path dependence play significant roles in the evolution of an NSI. This means that national systems can be radically different. Indeed optimal policies for one era or region may not be appropriate in a different context. Improving a country's innovative competence is not simply a matter of increasing innovation inputs, although the volume of innovation inputs is certainly important. Innovative competence also depends on the presence of dynamic Science, Technology and Innovation (STI) actors, operating within the confines of compatible institutions and with systemic linkages inducing the accumulation and diffusion of knowledge.

### *4.1 NSI: A Conceptual framework*

It may be helpful to imagine the economy as a system consisting of multiple elements along with the connections between those elements. The elements are individuals and organizations and they are subject to bounded rationality (Kahneman, 2003). The number of potential innovations the system can produce is virtually unlimited. Each element possesses its own finite and unique set of ideas at any one time and these individuals and organizations learn and acquire knowledge from each other. One implication (Cowan, 2004) is that densely interconnected systems will generate a higher rate of innovation than sparsely connected systems.

The government will always be the NSI's key actor. Governments can use fiscal and other policies to address systemic market failures related to the underproduction and slow diffusion of knowledge and innovation. It can also support enterprises in the development of their own innovation and technology absorption capacities. Finally, the government plays a key role in the development of innovation inputs, most importantly, through its funding of R&D, education, and other knowledge infrastructure.

The scale and types of the knowledge flows in the economy, as well as the nature, density and strength of the relationships between people and organizations are crucial. Slightly refining the conceptual framework described by Pontikakis, McDonnell and Geoghegan (2005, 2006), we can say that a system of innovation comprises:

i. The organizations and other actors engaged in innovation related activities
ii. The institutional environment in which these actors operate and
iii. The linkages between these actors including collaborations

The nature of the interactions between the various actors will help determine the success or otherwise of the NIS in delivering innovation.

NSI supporting institutions include the public administration apparatus; the financial system; the legal and regulatory framework; cultural attitudes, and the education system. However, the presence of well-functioning and compatible institutions merely *permits* the development of a successful NIS. They do not themselves deliver innovation. Ultimately, the actions of the STI actors will propel innovation.

STI actors include policy makers and policy enactors, as well as technology lobbyists, technology users and technology producers (see Table 4.1). Central government and subsidiary public sector bodies are obviously key actors within the system. Industry, including indigenous and multinational enterprises but also lending institutions such as venture capital funds and investment banks, and academia, including universities, institutes of technology and other research centres, are all crucial STI actors as technology users, producers and lobbyists.

STI funders (mainly but not exclusively policy makers and policy enactors) provide resource inputs while STI performers (technology producers such as universities and private enterprises) provide innovation outputs. Different actors will have different incentives for engaging in innovation. For example, policy makers in government might focus on job creation and economic growth, whereas private sector technology producers are more likely to focus on profits and their own capacity building. Government funding for innovation can be direct in the form of subsidies for the education sector, R&D and technology transfer, or can be indirect in the form of tax exemptions for R&D costs and special depreciation rates for R&D capital.

**Table 4.1 STI Actors within the Innovation System**

| STI Actor Role | Examples | Sample Contributions |
|---|---|---|
| Policy Maker | Government & Government Departments | Funding/strategic direction |
| Policy Enactor | Public Agencies | Regulation/coordination |
| Tech Producer | Enterprises and Academia | Knowledge/skills/products |
| Tech User | Foreign and Domestic Markets | Demand/spillover |
| Tech Lobbyist | Academia/Industry Associations/Consumer Groups | Analysis/information/demand |

**Source**: Table developed from Pontikakis et al., (2005)

An important difficulty when setting policy is that the socially optimal allocation of resources to innovation inputs is unknown in advance. The 'uncertainty in production' merely tells us that the market will under produce the socially optimal amount of innovation, but not the degree to which it will under produce. Innovation policy in the form of state support to industry can also lead to moral hazard issues. For example, corporate reallocation of intellectual property assets between companies in the same group but different countries in order to avail of a tax break will likely have no impact on global innovation production and will merely shift taxation from multinationals to households.

The various actors will also have differing motivations and incentives to engage in collaboration. Motivations can vary from increased profits to job creation. Engagement in innovation need not translate into collaboration and innovation policy must take account of the various motivations. Lack of awareness of potential opportunities is a major barrier to collaboration, particularly when it comes to firms with low absorptive capacity operating without specialist staff. Academic institutes can play an important role as networking, information sharing and collaboration nodes with outreach programmes for Small and Medium Sized Enterprises (SMEs) within their region.

## 5. UNDERSTANDING TECHNOLOGY DIFFUSION

The origin of technological change is an issue of fundamental importance for human wellbeing. W. Brian Arthur puts it this way:

> *...at the very core of where technology is generated, at the very core of the process that over decades generates the structure of the economy and the basis of our wellbeing, lies a mystery. From what process then...from what source...do the devices, methods and products that form the economy originate (Arthur, 2009, p. 108)?*

However, no matter how useful a technology is, its impact will ultimately depend on its level of diffusion and pervasiveness within the economy and society. Technology diffusion is an intrinsic part of the innovation process. Bronwyn Hall (2004) describes technology diffusion as the process by which individuals and firms in an economy adopt novel technologies or replace older technologies with improved versions. Learning in different contexts, along with imitation and feedback effects, will not only enhance the original innovation, but will spawn new ones. We can expect innovations to spread through the economy when they are clearly superior to previous technologies. This may occur via *learning-by-observing* processes in the Darwinian sense described by Richard Nelson and Sidney Winter (1982), and by Mokyr (1992). However, as Rosenberg (1972) points out, the diffusion process can take a long time with no guarantee of success.

Useful ideas have historically spread through observation and communication. New ideas almost always originate, in one form or another, from the ideas of other people. Certain human environments such as cities (Lucas, 1988) and the World Wide Web (Johnson, 2010) are more conducive to knowledge and idea spillover than other environments. This is because such environments provide physical or virtual proximity to other people and therefore to other people's ideas. They also provide opportunities for collaboration and cross-fertilisation of ideas.

A wide variety of historical trends facilitated the diffusion of knowledge and it may be unwise to rely on a single methodological framework to fully understand and explain the phenomenon of technology diffusion. So how can we explain differences in the diffusion of technology and new ideas? Economic theory provides us with a number of different insights.

There has been a wide variation in the rates and speed of acceptance of even successful innovations. Zvi Griliches (1957) and Edwin Mansfield (1963) find that successful technologies tend to exhibit a path dependent S-shaped diffusion curve over time. Numerous empirical studies have since confirmed the S-shaped diffusion curve. What causes the variation in the diffusion processes of different technologies? It may be that the diffusion process is influenced by the characteristics of the technology itself, such as its complexity, trialability, and observability, as well as by certain characteristics of potential technology adopters, for example their income levels and their levels and types of educational attainment. The wider socio-economic environment will presumably influence the diffusion process, as will the density and nature of social networks (Rogers, 2003). For example, Austan Goolsbee and Peter Klenow (2002) in a study of home computer adoption, found the influence of friends and neighbours had a significant positive effect on adoption decisions. The effect was present even after controlling for income, price and demographic effects.

Bronwyn Hall (2005) identifies four categories of factors, which, she argues, influence the diffusion path of innovations. Hall's four categories are:

a. Factors influencing the **perceived benefits** received from adopting the innovation,
b. Factors influencing the **perceived costs** of adopting the innovation,
c. Factors related to the **industrial and social environment** and
d. Factors related to **uncertainty and information problems**.

In addition, Everett Rogers (1995) has identified a number of technology characteristics, which, he argues, influence the decisions of potential adopters. They are:

1. Relative advantage over other technologies,
2. Compatibility with existing norms and practices,
3. Complexity,
4. Trialability and
5. Observability.

Some of these factors may change over time. Such changes will influence the diffusion process. For example, the relative advantage of a new product may be quite small to begin with but its benefits may subsequently increase over time as the technology is gradually improved and as more and more applications for the technology are developed. The benefit of the product may also increase as the number of users increases, a phenomenon known as a positive network effect. This effect may be particularly relevant for communication goods where there are likely to be direct network effects. Relative advantage will also improve if the cost of a new technology declines over time. This could happen, for example, if the production process is improved or if larger market size generates economies of scale.

Paul Geroski (2000) describes a number of models of technology diffusion. The two most influential of these models are:

A. The *epidemic model* based on awareness of the technology. We can imagine the technology being transmitted like an infection through social networks and other channels of communication, and
B. The *discrete choice* or *probit model* based on heterogeneous but rational firms and consumers adopting the technology when their expected net benefit from doing so exceeds the perceived opportunity cost. Expected net benefits will depend on the potential adopter's particular characteristics including their knowledge, biases, preferences and capabilities.

The epidemic model emphasizes the importance of awareness for technology diffusion and suggests the possibility that a relative lack of firm and/or consumer awareness of the benefits of a technology may explain a relatively slow rate of diffusion (Stoneman, 2001). On the other hand, the discrete choice model emphasizes that certain characteristics of consumers may influence technology adoption decisions; examples include available financial resources (Flamm, 2005) and level of education (Grosso, 2006).

More recent diffusion models drawing on principles from complexity theory include:

C. The *complex network models* which show how network relations between innovating agents affect the rate of innovation (Cowan, 2004), and
D. The *percolation models,* which show how the diffusion process can exhibit regional variation with widespread diffusion in some areas and low levels of diffusion in other areas (Frenken, 2006).

## *5.1 Factors underlying diffusion at the macro level*

### *5.1.1 Transport and communication technologies*

The genetic mutations enabling polysyllabic speech first occurred around two hundred thousand years ago. This development allowed efficient communication of complicated concepts and ideas (Botha and Knight, 2009). The subsequent development of a series of information and communication technologies has heavily influenced the historical diffusion or spread of new ideas, not to mention the preservation of existing ideas (Mokyr, 1992). Improvements in communication technologies (e.g. the printing press, the telegraph, and the internet) have transformed the codification, transmission and diffusion of new knowledge, and have increased the durability of existing knowledge. Improvements in communication technologies increase the connectivity of individuals and organizations and in so doing increase the density of the economic system. This facilitates the transmission and observability of useful ideas and therefore the diffusion of innovations. Advances in transport technologies such as the steam engine and the railroad have similarly helped increase connectivity and in so doing facilitated the spread of ideas and technology.

Kevin O'Rourke and Jeffrey Williamson (2001) describe how advances in communication and transport technologies facilitated the trend towards globalisation in the nineteenth century, the commensurate shrinking of the world, and the increased awareness of the ideas of other cultures. Advances in communication technology continued in the twentieth century. Bart Van Ark, Abhay Gupta and Abdul Erumban (2011) argue the development of the microprocessor in the 1950s has had a greater transformative effect on the economy than the development of any other information and communication technology in the past. While this position is undoubtedly controversial, the invention of the microprocessor certainly initiated the development of a series of incremental innovations, which in time was to lead to the development of both personal computers and to the Internet.

A contemporary example is broadband access technology. Broadband is important because it provides access to the World Wide Web and other online applications. This access increases the stock of knowledge available to any given individual. Broadband also reduces some of the barriers and costs associated with accessing knowledge. In so doing, broadband facilitates the diffusion of the global stock of knowledge and increases the probability of a randomly chosen individual exploiting a randomly chosen idea for economic or other advantage.

### *5.1.2 Proximity to other people*

Michael Kremer (1993) argues that the rate of innovation is a function of population size. His point is that each person has a non-zero chance of adding to the stock of knowledge as well as a non-zero chance of applying pre-existing knowledge in a novel context for economic gain. The heterogeneity of diverse economic actors is a potential source of innovation. Diverse and cosmopolitan societies are more likely than closed and parochial societies to produce their own innovations and to embrace external ideas. Jared Diamond

(1997) shows how regions with higher population densities have consistently produced new technologies at exponentially faster rates than regions with lower population density. The spillover concept is useful as an explanation for this phenomenon (Lucas, 1988). Greater proximity to other people makes you more likely to become aware of other people's ideas and knowledge and thus more likely to adopt those ideas or even potentially combine those ideas with other ideas as new ideas.

Bettencourt, Lobo, Helbing, Kuhnert and West (2007) have found that the per capita level of innovation is higher in locations with large populations and large population densities such as cities. They also find that there is super-linear scaling of innovation in urban environments meaning that, for example, a city that is ten times larger than its neighbor will be more than ten times as innovative.

An important implication for policy is that by enhancing the density and proximity of connections within the economic system we can also enhance the rate of innovation and long-run growth. In recent times, the wide-scale availability of fast and reliable Internet access technologies has increased the effective population, as well as the effective population density of the environment to which people have proximity. Of course, this is a virtual proximity as opposed to physical proximity. Even so, in some sense the Web functions like a virtual city (Johnson, 2010). Access to the Web connects previously semi-isolated local and regional economies into a more closely integrated global economy. For each regional economy, the stock of knowledge from which we can produce innovations expands, thereby increasing the number of feasible innovation possibilities.

### *5.1.3 Education and human capital*

We can use skill levels and educational attainment as proxies for what the OECD (1998) term human capital. Human capital represents the knowledge, skills, competences and creativity of individuals that is relevant to economic activity. We can assume that human capital is associated with a greater capacity to identify, adopt and use new technologies. Certain types of learning and experience may also facilitate creativity and greater openness to new ideas. Indeed Barro and Sala-i-Martin (2003) consider human capital a necessary input for, and complement to, innovation and technology diffusion.

There is evidence that strong education systems are associated with increases in the long-run per capita growth rate (Hanushek and Wößmann, 2007). Skill levels and cognition for the population as a whole (i.e. not just the top of the achievement distribution) appears to exert a positive effect on growth. Learning-by-doing (Arrow, 1962 and 1991) and life-long training and up-skilling are both relevant to technology diffusion to the extent that they expose individuals to new ideas and practices. Caselli and Coleman (2001) find that differences in human capital and educational attainment explain much of the variation in technology adoption rates between firms.

#### *5.1.4 The institutional environment or 'the rules of the game'*

The surrounding institutional environment influences technology diffusion. What do we mean by the 'institutional environment'? Each society operates under its own set of economic, legal and cultural 'rules of the game' which Douglass North (1990) terms institutions. The scale of diffusion depends on how the rules of the game incentivize and facilitate, or otherwise, the production and diffusion of innovation. The rules of the game depend not just on the market and on market players but also the institutional constraints. Examples of institutions include, amongst other things:

A) the education system,
B) the strength and predictability of property rights,
C) the workings of the financial system,
D) the regulatory system,
E) the pervasiveness of corruption,
F) the quality of governance,
G) the level of political stability,
H) fiscal policy including the availability of subsidies and the design of the tax system,
I) The legal system including the existence of patent law, as well as social and cultural norms (World Bank, 1997).

The prevailing set of institutions influence the costs and benefits of engaging in knowledge production and other innovative activities and in so doing influence the overall rate of innovation. The costs of knowledge search and knowledge production are crucial determinants of the volume of innovative activity as the profits from an idea provide much of the incentive to innovate. A falling net cost for knowledge acquisition means higher expected returns to innovative effort and, ceteris paribus, a higher volume of innovative effort.

### *5.2 Models of technology diffusion*

Successful instances of technology diffusion tend to exhibit an S-shaped diffusion curve. We can explain the S-shaped diffusion curve by a variety of different models. There are a number of surveys of technology diffusion models, for example, by Massoud Karshenas and Paul Stoneman, (1995); by Paul Geroski, (2000), and by Stoneman (2001). Geroski (2001) describes a number of models. The two most influential diffusion models are the epidemic model and the discrete choice or probit model.

According to the **epidemic model** consumers learn about the new technology at different times and the diffusion of information about the technology limits the overall level of adoption. In the simplest version of the epidemic model, awareness of the technology is the principal factor determining adoption patterns. We assume consumers adopt the technology when they become aware of it. Awareness of the new technology transmits like an infection through social networks, or through other channels of communication. The probability of acquiring the infection increases over time as the percentage of the population carrying the infection increases. During the early phase of the diffusion process, the rate of new adoptions will increase in each period. This is because the rate of infection increases in each period. However, the number of people not yet infected, yet susceptible to the infection, is also declining over time. When we reach a certain threshold, the negative effect exerted by the decline in the number of new potential carriers will exceed the positive effect exerted by the higher probability of a given individual acquiring the infection. When we reach this point, the market will reach saturation. This process generates the S-shaped diffusion curve.

The main alternative to the epidemic model is the **discrete choice or 'probit' model**. Discrete choice models assume the decision to adopt a technology is a rational choice made by a particular individual, firm or institution. The probit model and the closely related logit model assume that consumers choose to adopt a new technology when their expected net benefit from adopting the technology exceeds their perceived opportunity cost. The adoption choice depends, amongst other things, on the particular characteristics of the individual or organisation including their knowledge, preferences and capabilities.

We assume the differences between consumers will partially explain technology adoption decisions and that the adoption event will occur when the expected benefit to the consumer from adoption x exceeds a threshold cost y. Suppose consumers differ in some bundle of known and unknown characteristics z, and that z positively affects the expected benefit x. We expect that consumers will adopt the technology provided the cumulative effect of z (consumer characteristics) on x exceeds some level y, i.e. if the consumers expected benefits x exceed the threshold cost y.

If the distribution of expected benefits exerted by the bundle of characteristics z has a normal distribution in the population, and the threshold cost y declines at a constant (monotonic) rate over time, then we derive a diffusion curve with the stylised S-shape. Alternatively, if the technology exhibits a direct network effect (see Shy, 2001) then the value of the product will increase, as more and more people become users. In this case, if the distribution of expected benefits over consumers has a normal distribution in the population, then the S-shaped diffusion curve generates as part of a feedback process regardless of whether costs decline over time.

There are also a number of diffusion models drawing on principles from complexity theory. For example, in the **complex network models**, Robin Cowan (2004) shows how network relations between innovating agents affect the rate of diffusion. Diffusion occurs when information or knowledge passes from one agent to another. Networks are fluctuating, dynamic and evolving over time. Diffusion of tacit knowledge within the network depends heavily on the nature of the network of agents through which it spreads. More dense networks of agents will exhibit higher rates of diffusion, while better-connected agents within the network are more likely to become technology adopters.

Koen Frenken (2006) shows how **percolation models** can explain the technology diffusion process. In the simplest percolation model, each individual agent has four neighbours. We assign each agent a different preference threshold p for the new technology or product, with preferences uniformly distributed in value between zero and one. If an agent becomes aware of the existence of the product then he or she will evaluate whether the product quality q is greater than his or her preference threshold p. If q is greater than p then the agent will adopt the product and will inform his or her four nearest neighbours of the product's existence. We can see that the maximum rate of adoption for the product is equal to the product quality q. However, the actual rate of adoption is likely to be lower than q because many agents will never find out about the product in the first place. An important result is that the diffusion process generated by the percolation model exhibits regional variation. Widespread diffusion of the technology may occur in certain regions while diffusion may be low in other regions.

### *5.3 Technology adoption: A conceptual framework*

At the organisational level the idea of 'absorptive capacity' is used to capture the ability of the organisation (e.g. a firm or public agency) to identify, value, assimilate and apply new knowledge (Cohen and Levinthal, 1990). Small enterprises in particular may have weak capacities and if the organisation lacks sufficient capacity the new idea or technology will fail to diffuse. The concept of absorptive capacity provides a rationale for government to publicise the potential benefits of new innovations; to provide high levels of funding for education in order to improve individual and general capacities; to encourage personnel mobility between academia and industry, and to establish and support flows of information between producers and potential users. The absorptive capacity concept can also be applied at the individual or consumer level.

There is a large body of empirical evidence relating to variations in technology adoption. At a geographic level, Tony Grubesic (2002) identifies differences in Internet activity between urban and rural locations in Ohio. The seminal work of Richard Nelson and Edmund Phelps (1966), and of Nathan Rosenberg (1972), finds that differences in human capital help explain variation in adoption rates between firms. The availability of finance also has implications for a firm's ability to invest in new technology. Edwin Mansfield (1964) and Eleonora Bartoloni and Maurizio Baussola (2001) find that firm size, which affects the availability of finance, positively influences a firm's propensity to adopt new technology. Paul David (1975) finds that because most costs of adoption are fixed, the adoption choice relates to the scale of the firm as well as to the market size and structure of the industry in which the firms operate. Francesco Caselli and Wilbur Coleman (2001) and Hyunbae Chun (2003) identify the importance of human capital and educational attainment for technology adoption at the firm level. In the Irish context, Stefanie Haller and Iulia Siedschlag (2007) identify unevenness in the adoption of ICTs across firms, industries and space, while Dimitrios Pontikakis and Patrick Collins (2010) find that firm level broadband adoption is uneven across industrial sectors. Haller and Siedschlag's results suggest that successfully adopting Irish firms tend to be larger, younger, fast growing, skills and export intensive, and located in Dublin.

We can draw on Kelvin Lancaster's hedonic demand theory (1966), as well as the discrete choice and epidemic models of technology diffusion, to help us better understand the technology adoption process. There are a number of requirements for a consciously made adoption decision to occur. These requirements include A) awareness, B) capacity, and C) a minimum expected net benefit on the part of the consumer. Adoption is also contingent upon D) availability. We can reasonably assume that differences in the characteristics of individuals will explain part of the variation in technology adoption and adoption decisions and that decision makers with different characteristics will have different odds of adoption at any given time.

Lancaster (1966) argues that consumers (or firms) making purchases are not seeking to acquire goods and services themselves. Rather, firms and consumers are seeking to acquire the characteristics contained within those goods and services. According to Lancaster, what firms and customers actually want is not so much a specific product, but the particular bundle of characteristics and the 'utility' provided by those characteristics. The assumption is consumers with perfect information can acquire any combination of characteristics they desire, subject only to budget and opportunity constraints.

Lancaster's hedonic demand theory is a revealed preference method of estimating the demand for, or value assigned to, a particular good or service. The hedonic demand theory decomposes the good or service into its constituent characteristics (such as life span and quality), and then obtains estimates of the contributing value of each characteristic. However, we cannot consider the expected benefits of different goods and services in isolation from their respective costs. If there were a relative increase in the cost of using a substitute good, then all things being equal we would expect the demand for our good to increase.

Everett Rogers (1983) argues that each potential technology adopter holds a unique perception of the technology's relative advantage. The perceived relative advantage is the total positive utility from the technology's characteristics that a potential adopter expects to enjoy, less the total expected costs involved including opportunity costs. We can assume a higher expected net benefit from adoption, i.e. the perceived relative advantage, is associated with a higher probability of adoption (Hall, 2005).

Consumers differ in their characteristics and therefore in their technology adoption decisions. Technology adoption requires a number of conditions. In Table 5.1, I present a framework for explaining technology adoption that draws on a number of principles such as those described in the epidemic and discrete choice models of technology diffusion. The framework presented is from McDonnell, (2013) and considers the issue of adoption from the perspective of the potential technology adopter (i.e., the consumer). I divide reasons for non-adoption into four categories. They are:

A. Issues related to **awareness** of the technology. As the epidemic models presume, the consumer must become aware of the existence of the technology. Consumers clearly will not adopt a technology if they are not aware of it.
B. The second category relates to **opportunity** and this includes issues of availability. It must be possible for the consumer to have the option of purchasing or otherwise obtaining the technology. Again, consumers clearly cannot adopt a technology if the choice to adopt is not available to them.
C. The third category relates to the consumer's **capacity to obtain the technology**, which may include financial issues. The consumer's capacity in terms of resources, financial and otherwise, will influence the consumer's decision to adopt or purchase the technology and may even completely preclude the possibility of adoption.
D. Finally, as the discrete choice models presumes, the consumer's perception of **the utility, or relative advantage, of the technology** will influence the adoption decision. This may include issues related to the consumer's preferences, experience or competence.

Technology adoption requires an affirmative response to the first three tests described in Table 5.1. In other words, awareness, opportunity and capacity are necessary but insufficient conditions for conscious adoption to occur.

The greater the expected utility the greater will be the consumer's probability of adoption. We can characterize each choice available to the consumer by a vector of n positive and negative attributes. For example, ease of use is a positive attribute while the monetary cost is a negative attribute. We then assume that the consumer will choose the discrete alternative he or she perceives will maximize his or her expected utility over the set of available alternatives. If both choices are available then adoption will occur if the consumer's perception of the expected net utility of adoption exceeds the expected net utility of non-adoption.

**Table 5.1 Questions or 'tests' underpinning the adoption decision**

| Category | Question | Factors |
|---|---|---|
| **A** | Is the consumer '**aware**' of the technology? | Education, Experience, Physical Location, Contact with existing Users |
| **B** | Does the consumer have the '**opportunity**' to acquire the technology? | Technological constraints, Infrastructure Constraints, Market Constraints, Legal Constraints, Physical Location |
| **C** | Does the consumer have the '**capacity**' to acquire the technology? | Cash flow, Income, Wealth, Access to finance, Education and Skill-set, Social Contacts |
| **D** | What is the consumer's anticipated level of '**utility**' from the technology? | Personal Preferences, Perceived Relative Advantage, Familiarity with Similar Technologies, Market Opportunities |

## 6. CONCLUSION

The preceding discussion outlines some of the main concepts and principles that policymakers can use as part of a framework for generating sustainable long-run economic growth. We can make a number of points. First, sustainable growth is dependent on continuous productivity gains arising from innovation. Second, innovation is itself a function of the production, diffusion and application of economically useful new ideas. Third, the characteristics of knowledge mean that the self-regulating market under-produces relative to the socially optimal level of innovations. This creates a rationale for direct (e.g. R&D spending) and indirect (e.g. fiscal supports) state intervention to boost knowledge production and diffusion and enhance the economy's innovative capacity. As a priority policymakers should focus on policies to reduce the net cost to engaging in innovation activities (e.g. access to broadband) and on policies that enhance the quality of innovation inputs (e.g. investments in education and in machinery and equipment).

Fourth, increasing innovation 'outputs' is not simply a matter of increasing innovation 'inputs' such as spending on R&D. Innovation is an iterative and adaptive process that occurs within a complex system characterized by a multiplicity of interactions between agents and by positive and negative feedback loops. Policymakers should ensure that the institutional environment incentivizes new thinking, collaboration and risk taking. This requires a supportive and transparent public administration; a well-functioning financial system; an appropriate regulatory and legal environment; a strong education system, and cultural attitudes that embrace risk taking, do not punish failure (e.g. through soft bankruptcy provisions) and have an open attitude to diverse opinions and migration.

Fifth, no matter how useful an innovation is, its impact will ultimately depend on its level of diffusion and its pervasiveness within the economy. A key task for policymakers is to encourage technology diffusion and adoption. Policies that effect communication technologies; proximity to other people and their ideas; education and human capital, and the economic 'rules of the game' are all likely to be relevant. Sixth, successful technology diffusion requires a positive adoption decision. The potential adopter, be it an enterprise or an individual, must first be aware of the technology. In addition, the potential adopter must have the opportunity and the capacity to adopt the technology. Finally, the adoption decision depends on the perception of the utility and opportunity cost of the technology.

This all suggests a number of potential policy levers. We can enhance awareness of new technologies and innovations through a public information campaign, or by improving the knowledge flows between economic actors. Opportunity to acquire technologies may be an issue of infrastructural or legal constraints. Policymakers have some control over these areas. Broadband is a contemporary example of a technology whose diffusion is limited in many countries due to lack of opportunity, particularly in rural areas. Capacity to acquire the technology, sometimes called absorptive capacity, may relate to financial constraints or human capital constraints. This suggests a rationale for directly subsidizing technology adoption by small firms, and for subsidizing training and up-skilling for workers and managers. In particular, this includes subsidization and other supports for green technologies (e.g. renewable energy, retrofitting, public transport) where there are likely to be positive environmental externalities associated with adoption and use. Finally, we can increase the perceived utility of the technology through public information campaigns and demonstration effects and through complementary investments in human capital

A final point is that optimal policies are context dependent. Specific policies proposals will depend on the existing industrial structure, the skill-base of the workforce, the macroeconomic climate and so on. Policies for the Republic of Ireland and for Northern Ireland are set out in McDonnell (2019, Forthcoming) and in McDonnell and Mac Flynn (2019, Forthcoming).

## REFERENCES


Abramovitz, M., 1956. Resource and Output Trends in the United States since 1870. American Economic Review, Papers and Proceedings of the American Economic Associations, 46, pp. 5-23.

Acemoglu, D., 2009. *Introduction to Modern Economic Growth*. New York: Princeton University Press.

Aghion, P. and Howitt, P., 1992. A Model of Growth through Creative Destruction. *Econometrica*, 60, pp. 323-351.

Aghion, P. and Howitt, P., 2009. *The Economics of Growth*. Cambridge: MIT Press.

Arrow, K. J., 1962. The Economic Implications of Learning by Doing. *Review of Economic Studies*, 29 (3), pp. 155–73.

Arrow, K. J., 1991. Returns to Scale, Information and Economic Growth. **In**: KDI, *The Twentieth Anniversary Symposium on Economic Growth of Developing Countries 1940s-1980s*. Seoul, Republic of Korea.

Arthur, W. B., 2009. *The Nature of Technology: What it is and How it Evolves*. New York: Free Press.

Bacon, F., 1597. Religious Meditations of Heresies. In: *The Collected Works of Sir Francis Bacon*. 2009. Houston: Halycon Press.

Barro, R. J. and Sala-i-Martin, X., 1995. Technological Diffusion, Convergence, and Growth. *NBER Working Paper*, 5151.

Barro, R. J. and Sala-i-Martin, X., 2003. Economic Growth. Second Edition. Cambridge, Massachusetts: MIT Press.

Bartoloni, E. and Baussola, M., 2001. The Determinants of Technology Adoption in Italian Manufacturing Industries. *Review of Industrial Organisation*, 19, pp. 305-328.

Bettencourt, L., Lobo, J., Helbing, D., Kuhnert, C. and West, G. B., 2007. Growth, Innovation, Scaling and the Pace of Life in Cities. *Proceedings of the National Academy of Sciences*, 104 (7).

Botha, R. P. and Knight, C., 2009. *The Prehistory of Language*. Oxford: Oxford University Press.

Bresnahan, T. F. and Trajtenberg, M., 1995. General Purpose Technologies: Engines of Growth? *Journal of Econometrics*, 65, pp. 83-108.

Caselli, F. and Coleman, W., 2001. Cross-country Technology Diffusion: The Case of Computers. *American Economic Review*, 91 (2), pp. 328-335.

Chun, H., 2003. Information Technology and the Demand for Educated Workers:

Disentangling the Impacts of Adoption versus Use. *The Review of Economics and Statistics*, 85, pp. 1-8.

Cohen, W. M. and Levinthal, D. A., 1990. Absorptive Capacity: A New Perspective on Learning and Innovation. *Administrative Science Quarterly*, 35(1), pp. 128-52.

Cowan, R., 2004. Network Models of Innovation and Knowledge diffusion. *MERIT – Infonomics Research Memorandum Series*, 2004-016, July.

Diamond, J., 1997. *Guns, Germs and Steel: A Short History of Everybody for the Last 13,000 Years*. London: Random House.

Dopfer, K., 2005. *The Evolutionary Foundations of Economics*. Cambridge: Cambridge University Press.

Easterly, W. and Levine, R., (2001). It's Not Factor Accumulation: Stylized Facts and Growth Models. *World Bank Economic Review*, 15 (2), pp. 129-158.

Edquist, C., 2004. Systems of Innovation. **In**: J. Fagerberg, D. C. Mowery and R. R. Nelson, eds. *The Oxford Handbook of Innovation*. Oxford: Oxford University Press.

Flamm, K., 2005. The Role of Economics, Demographics, and State Policy in Broadband Availability. **In**: PURC/London Business School conference, *The Future of Broadband: Wired and Wireless*. Gainesville, Florida.

Furman, J. L., Porter, M. E. and Stern, M. E., 2002. The Determinants of National Innovative Capacity. *Research Policy*, 31, pp. 899-933.

Freeman, C., 1991. Networks of Innovators: A Synthesis of Research Issues. *Research Policy*, 20 (5), pp. 499-514.

Frenken, K., 2005. *Innovation, Evolution and Complexity Theory*. Cheltenham: Edward Elgar.

Frenken, K., 2006. Technological Innovation and Complexity Theory. *Economics of Innovation and New Technology*, 15 (2), pp. 137-155.

Geroski, P. A., 2000. Models of Technology Diffusion. *Research Policy*, 29 (4-5), pp. 603-625.

Griliches, Z., 1957. Hybrid Corn: An Exploration in Economics of Technological Change. *Econometrica*, 25, pp. 501–02.

Grossman, G. M. and Helpman, E., 1991. *Innovation and Growth in the Global Economy*. Cambridge, Massachusetts: MIT Press.

Grubesic, T. H., 2002. Spatial Dimensions of Internet Activity. *Telecommunications Policy*, 26 (7-8), pp. 363-387.

Hall, B. H., 2004. Innovation and Diffusion. **In:** J. Fagerberg, D. C. Mowery, and R. R. Nelson, eds. *The Oxford Handbook of Innovation*. Oxford: Oxford University Press.

Grosso, M., 2006. Determinants of Broadband Penetration in OECD Nations. *Regulatory Development Branch, Australian Competition and Consumer Commission, 2006*

*Communications Policy and Research Forum*.

Haller, S. and Siedschlag, I., 2007. Determinants of ICT Adoption: Evidence from Firm-Level Data. *ESRI Working Paper No. 204*, July. Dublin: ESRI.

Hanusch, H. and Pyka, A., 2005. Principles of Neo-Schumpeterian Economics. *Volkswirtschaftliche Diskussionreihe*, Beitrag No. 278, September.

Hanushek, E. and Wößmann, L., 2007. The Role of Education Quality in Economic Growth, *World Bank Policy Research Working Paper No. 4122*, February. Washington: World Bank.

Helpman, E. and Trajtenberg, M., 1998. Diffusion of General Purpose Technologies. **In**: E. Helpman, ed. *General Purpose Technologies and Economic Growth*. Cambridge: MIT Press.

Jacobson, D. 2013. Innovation Policy and Performance in Ireland, **In**: D. Jacobson ed. *The Nuts and Bolts of Innovation*. Dublin: Glasnevin Publishing.

Johnson, S., 2010. *Where Good Ideas Come From: The Seven Patterns of Innovation*. London: Penguin.

Jones, C. I. and Williams, J. C., 1998. Measuring the Social Return to R and D. *Quarterly Journal of Economics*, 113 (4), pp. 1119-1135.

Kahneman, D., 2003. Maps of Bounded Rationality: Psychology of Behavioural Economics. The *American Economic Review*, 93 (5), pp. 1449-1475.

Kahneman, D., 2011. *Thinking Fast and Slow*. London: Allen Lane.

Kaldor, N., 1957. A Model of Economic Growth. *Economic Journal*, 67, pp. 591-624.

Karshenas, M. and Stoneman, P., 1995. Technological Diffusion. **In**: P. Stoneman, ed. *Handbook of the Economics of Innovation and Technological Change*. Oxford: Blackwell.

Kremer, M., 1993. Population Growth and Technological Change: One Million BC to 1990. *The Quarterly Journal of Economics*, 108 (3), pp. 681-716.

Lancaster, K. J., 1966. A New Approach to Consumer Theory. *Journal of Political Economy*, 74, pp. 132-157.

Lucas, R., 1988. On the Mechanics of Economic Development. *Journal of Monetary Economics*, 22, pp. 3-42.

Lundvall, B. A., 1992. *National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning*. London: Pinter.

Mankiw, N. G., Romer, D. and Weil, D. N., 1992. A Contribution to the Empirics of Economic Growth. *Quarterly Journal of Economics*, 107 (2), pp. 407-437.

Mansfield, E., 1963. Intra-firm Rates of Diffusion of an Innovation. *The Review of Economics and Statistics*, 45 (4), pp. 348-59.

McDonnell, T., 2013. *The Economics of Broadband in Ireland: Country Endowments, Telecommunications Capital Stock, and Household Adoption Decisions*. NUI Galway, PhD

Thesis. Galway: J.E. Cairnes School of Business and Economics.

McDonnell, T. 2017. Innovative Competence, How does Ireland do and does it Matter? *NERI Working Paper*, No. 40 (January).

McDonnell, T. and Goldrick-Kelly, P., 2018. A Growth Friendly Composition? Breaking down Public Spending in Ireland. *Journal of Self-Governance and Management Economics,* 6 (3), pp. 7-34.

McDonnell, T. 2019. Building an Entrepreneurial State: What are the options for the Republic of Ireland? NERI Working Paper, No. xx (April).

McDonnell, T., and P. Mac Flynn 2019. An Enterprise Strategy for Northern Ireland and the Republic of Ireland: Some Proposals. NERI Working Paper, No. xx (July).

Metcalfe, J. S. and Georgiou, S., 1997. Equilibrium and Evolutionary Foundations of Technology Policy. *CRIC Discussion Paper*, No. 3, September.

Mokyr, J., 1992. *The Lever of Riches: Technological Creativity and Economic Progress*. Oxford: Oxford University Press.

Mokyr, J., 2002. *The Gifts of Athena: Historical Origins of the Knowledge Economy*. New York: Princeton University Press.

Nelson, R., 1993. *National Systems of Innovation: A Comparative Analysis*. Oxford: Oxford University Press.

Nelson, R. R. and Phelps, E. S., 1966. Investing in Humans, Technological Diffusion, and Economic Growth. *American Economic Review*, 56, pp. 69-75.

Nelson, R. and Winter, S., 1982. *An Evolutionary Theory of Economic Change*. Cambridge, Massachusetts: Harvard University Press.

North, D. C., 1990. *Institutions, Institutional Change and Economic Performance*. Cambridge: Cambridge University Press.

OECD, 1998. Human Capital Investment: An International Comparison. Paris: OECD.

O'Rourke, K. and Williamson, J. G., 2001. *"Globalization and History: The Evolution of a Nineteenth-Century Atlantic Economy*. Cambridge, Massachusetts: MIT Press.

Pontikakis, D. and Collins, P., 2010. Exploring Geographic Variation in Corporate Broadband Adoption; Evidence from Irish Small-and-Medium Sized Enterprises. *Telecommunications Policy*, 34 (3), pp. 144-161.

Pontikakis, D., McDonnell, T. and Geoghegan, W. 2005. A Look at Ireland's National Innovation System, CISC Seminar Series. Galway, Ireland.

Pontikakis, D., McDonnell, T. and Geoghegan, W. 2006. Ireland's National Innovation System: An Exploratory Study of Supporting Institutions and Dynamic Actors. Prometheus: Critical Studies in Innovation, 24(1), pp. 37-58.

Ray, D., 1998. *Development Economics*. Princeton: Princeton University Press.

Rogers, E., 2003. *Diffusion of Innovation*. New York: Free Press.

Romer, P., 1986. Increasing Returns and Long-Run Growth. *Journal of Political Economy*, 94 (5), pp. 1002-1037.

Romer, P., 1990. Endogenous Technological Change. *Journal of Political Economy*, 98, pp. 71-102.

Romer, P., 1992. *Two Strategies for Economic Development: Using Ideas and Producing Ideas*. **In**: World Bank, Proceedings of the World Bank Annual Conference on Development Economics. Washington DC, United States.

Romer, P., 1993. Idea Gaps and Object Gaps in Economic Development. *Journal of Monetary Economics*, 32, pp. 543-573.

Rosenberg, N., 1972. Factors Affecting the Diffusion of Technology. *Explorations in Economic History*, 10 (1), pp. 3-33.

Ruttan, V. W., 2008. General Purpose Technology, Revolutionary Technology, and Technological Maturity. *University of Minnesota Staff Paper P08-3*, April.

Schumpeter, J., 1942. *Capitalism, Socialism and Democracy*. New York: Harper & Brothers.

Shy, O., 2001. *The Economics of Network Industries*. Cambridge: Cambridge University Press.

Snowdon, B. and Vane, H. R., 2005. *Modern Macroeconomics: Its Origins, Development and Current State*. Cheltenham: Edward Elgar.

Stoneman, P., 2001. *The Economics of Technological Diffusion*. Oxford: Blackwell Publishers.

Van Ark, B., Gupta, A. and Erumban, A. A., 2011. Measuring the Contribution of ICT to Economic Growth. **In**: B. Van Ark, R. Weiss, and K. Schinsai, eds. *The Linked World: How ICT is Transforming Societies, Cultures and Economies*. Madrid: Ariel and Fundacíon Telefonica.

Verspagen, B., 2004. Innovation and Economic Growth. **In**: J. Fagerberg, D. C. Mowery, and R. R. Nelson, eds. *The Oxford Handbook of Innovation*. Oxford: Oxford University Press.

Warsh, D., 2006. *Knowledge and the Wealth of Nations: A Story of Economic Discovery*. New York: W. W. Norton.

Whitt, R. S, 2009. Evolving Broadband Policy: Taking Adaptive Stances to Foster Optimal Internet Platforms. *CommLaw Conspectus*, 17 (417), pp. 417-534.

World Bank, 1997. *The State in a Changing World*. Oxford: Oxford University Press.

Young, A., 1928. Increasing Returns and Economic Progress. *The Economic Journal*, 38 (152).

**RECENT NERI WORKING PAPERS**

The following is a list of recent research working papers from the NERI. Papers are available to download by clicking on the links below or from the NERI website:

| Number | Title/Author(s) |
|---|---|
| **2018:** | |
| **57** | Productivity on the island of Ireland – A tale of three economies - Paul Goldrick-Kelly & Paul Mac Flynn |
| **56** | Housing Affordability for Ireland's Young People in the Context of the Cost of Living: A Long-Term Assessment – Dara Turnbull |
| **55** | 'Bad' jobs and productivity: The flexibility paradox - Paul Mac Flynn & Lisa Wilson. |
| **54** | Equality in Irish Healthcare – Time for a New Deal - Paul Goldrick-Kelly & Tom Healy |
| **53** | Labour Market Trends in the Republic of Ireland - Thomas A. McDonnell & Ciarán Nugent |
| **52** | Housing Provision in Northern Ireland and its implications for Living Standards and Poverty – Paul Mac Flynn & Lisa Wilson. |
| **51** | Wage sufficiency in the context of the Irish Housing Emergency: Rents and Access to homeownership - Ciarán Nugent |
| **2017:** | |
| **50** | The gendered nature of employment and insecure employment in Northern Ireland: A story of continuity and change - Lisa Wilson |
| **49** | A Low skills equilibrium in Northern Ireland? - Paul Mac Flynn |
| **48** | Taxation and Revenue Sufficiency in the Republic of Ireland - Paul Goldrick-Kelly & Thomas A. McDonnell |
| **47** | Northern Ireland, the Republic of Ireland and the EU Customs Union - Paul Mac Flynn |
| **46** | Public Spending in the Republic of Ireland: A Descriptive Overview and Growth Implications– Thomas A. McDonnell & Paul Goldrick-Kelly |
| **45** | Patterns and Trends in employment arrangements and working hours in Northern Ireland – Lisa Wilson |
| **44** | A long-term assessment of Irish house price affordability - Dara Turnbull |
| **43** | A time series analysis of precarious work in the elementary professions in Ireland– Ciarán Nugent |
| **42** | Industrial Policy in Northern Ireland: A Regional Approach - Paul Mac Flynn |
| **41** | Ireland's Housing Emergency – Time for a Game Changer - Tom Healy & Paul Goldrick-Kelly |
| **40** | Innovative Competence, How does Ireland do and does it matter? – Thomas A. McDonnell |

For earlier NERI Working Papers see http://www.nerinstitute.net/research