Technology successions and policies for promoting more environmentally friendly technologies

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1. Introduction

This paper is a contribution to the Netherlands Environmental Assessment Agency project ‘Environmental policy and modelling in evolutionary economics’. The core thesis of this paper is that policy-makers, firms and consumers are the agents of path dependencies that main support and maintain technological paradigms. They are also the agents of change. The replacement of old technology paradigms by new paradigms occurs when there are fundamental changes in the expectations, preferences, competences and policies of these agents.

In Windrum (1999), I made the point that past research on the diffusion of new technologies ignores the existence of powerful path dependencies that build up around established technologies and lock-out new technologies. At that time, a body of research existed on path dependency in contemporaneous competitions between rival variants of a new technology. However path dependency was not being considered in relation to sequential competitions between old and new technologies. Implicitly, it was assumed that path dependencies did not matter. The notable exception was David’s 1985 paper on the lock-out of the DVORAK keyboard by the QWERTY keyboard. It highlighted the need for research into this issue.

My 1999 paper began to explore factors of path dependency that affect the probability of new technology adoptions. I started out by making a link with evolutionary ecology. Traditional diffusion models are best suited to discussions of ‘early colonists’, i.e. the very first technologies that establish themselves in virgin territory and, hence, are not competing with pre-established technologies. Subsequent technologies, however, must directly compete with, and displace, established technologies. This is the basis of a ‘technology succession’. A succession is difficult because path dependency means the selection environment – made up of firms, consumers and policy makers – has a predisposition in favour of the old technology. In other words, the selection environment is less open to radical new technologies than it was in earlier stages. The new technology must do something novel and different. This was the starting point for my subsequent research in this area.

The first part of this paper (sections 2 to 4) reviews the research on path dependency in sequential technology competitions that has been conducted since 1999. The second part of the paper (sections 5 and 6) develops a co-evolutionary framework that captures the dynamics of successions. This can be used by those interested in promoting more environmentally friendly technologies. Section 2 reviews existing research on the sources of market path dependency by firms and consumers. I extend the discussion to consider the key role played by the path dependencies of policy makers and how this helps to establish and maintain a technological trajectory. There is an important shift in perspective here. Rather than viewing the policy maker as an independent rational planner, we need to view the policy-maker as an interconnected agent within a complex selection environment that comprises firms, consumers and policy makers.

Section 3 discusses a set of conditions for a technology succession - i.e. the conditions that are necessary for a new technology to displace an established technology. This is derived from theoretical papers by Shy (1996), Malerba et al. (1999), Saviotti and
Pyka (2004), and Windrum and Birchenhall (2005), and from empirical research conducted by Islas (1997), Yamamura et al. (2005), and Windrum (2001, 2004, 2005). Section 4 identifies a set of strategies that have been successfully used by firms to break the path dependencies supporting established technologies. Understanding these strategies, and the basis of their success, is essential for policy-makers interested in promoting new, more environmentally friendly technologies.

Section 5 introduces a co-evolutionary framework that comprises policy makers, consumers and firms. It begins by outlining the general approach of interacting agents operating within a complex selection environment. Section 5.1 discusses two case studies, the evolution of the car-based transport system and refrigerants. The cases studies provide us with a set of stylised facts that are to be captured in the formal framework. These concern the behaviour and actions of agents, and the interactions between agents. Section 5.2 proceeds to formalise these behaviours, actions and interactions for each of the three key agents: policy makers (5.2.1), consumers (5.2.2), and firms (5.2.3). A number of core key concepts and ideas are introduced at this stage: trans-trajectory or ‘deep’ path dependency, conceptual innovation, new consumption possibilities facilitated by new technologies, and the co-evolutionary learning of adaptive agents in dynamic, changing environments. Section 6 concludes by identifying a set of policy lessons that can be gleaned from this approach, and the set of instruments that can be used by policy makers to promote technology successions.

It is important to clearly define the scope of this research. The focus here is sequential technology competitions and, more specifically, the conditions under which new technologies can displace established technologies. In a sense, this research topic harks back to an old research question, one that dates back to Schumpeter (1912, 1939) and was restated and reinvigorated in the work of Freeman (Freeman 1982; Freeman et al.1982). This older research question concerns the periodic introduction of key new technologies that set into train long-run economic cycles, known as ‘Kondratiev Waves’. As stated earlier, the focus here is not on the periodicity of new technologies but on the conditions under which new technologies are able to displace old, established technologies in sequential competitions. This is a key issue for policy-makers and all others interested in the promotion of new, more environmentally friendly technologies.

What are the essential features of technology competitions? Not all competitions between rival products are included in the definition of ‘technology competitions’. Technologies competitions are a particular subset of product competition. Technology competitions have two particular features. First, there is a technical differentiation (non-compatibility) between the competing technologies. For instance a DVD disk is incompatible with a VCR player. iPods do not play CDs. Second, there tend to be significant switching costs for adopters. New technology goods tend to be expensive, and there are invariably non-pecuniary set-up costs associated with learning how to use a particular technology product. It is due to both technical incompatibilities and the existence of switching costs between rival technology products that technology competitions are zero sum games, i.e. they are winner-takes-all competitions.

Technology competitions are important for technical, commercial and policy reasons. Technically, standards are essential for the integration and development of
technological systems. The internet, for example, is a complex technology that comprises numerous interacting components. In order for the internet to work, content (media and services), hardware (cables, routers, servers, PCs), software (operating systems, browsers, and e-mail), communication protocols (WWW and TCP/IP), and design conventions (that provide website ergonomics and functionality to the user) must all interface and work together. In terms of commercial advantage, the proprietary ownership and control of a standard technology is a key strategic device through which a firm can influence and control an industry. For instance, the term ‘WINTEL PC’ indicates the two key corporations that control the PC industry by virtue of having proprietary control of the underpinning operating system and chip set technologies. Finally, technology competitions have significant implications for policy making. Policy makers must operate within an envelope of possible options that are set by technologies. Technologies are one important factor that frames and gives direction to policy. Alternative technologies tend to be associated with different envelopes, and so policy makers are deeply interested in the different possibilities associated with new and/or alternative technologies.

It is also important to clarify the phase of technology development that is being considered. Here we are specifically concerned with the diffusion of a new technology. This is the third, and final, phase of technology development discussed by Schumpeter (1912, 1939). The first phase, invention, is usually related to some empirical or scientific discovery. In itself, an invention has no economic or social significance, and typically offers no hints about possible applications. The second phase, innovation, is the point at which the invention is actually applied for the first time, whether this takes the form of a product or a process. The first applications of a technology are invariably crude and inefficient. Not only is their performance usually poor compared to existing (alternative) technologies, but the (fixed) production costs are likely to be very high. Hence, innovations are not automatically capable of diffusing. They are like swan’s eggs, requiring a (possibly long) gestation period in which further basic research and development is needed to develop them. If this is not possible, they will perish. Rosenberg (1982) observes that survival of the new technology requires the establishment of a protected space in which further development can be achieved. This can take the form of distinct niche or sub-niche in the market, which may be complementary to the established technology, or else take the form of public sector support, where users are often also contributors to the R&D process (Hoogma et al., 2002; Geels, 2005).

Our focus is on the third phase of a new technology, its diffusion. Diffusion involves the widespread assimilation of a technology within a politico-socio-economic setting. To carry on the analogy of the swan’s egg, an innovation is an attractive duckling at the outset of this diffusion stage. This highlights an important difference between the innovation phase and diffusion phase of a technology life cycle. In the innovation phase, a technology will survive provided it shows sufficient promise or potential to a key group of supporters – even if it is initially inferior in many respects to the old technology. In the diffusion phase, new technology goods must directly compete on quality and price with old technology goods in the mass market. While the mass

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1 Less poetically, Mokyr (1990) calls them ‘hopeful monstrosities’. ‘Hopeful’ because they have particular features that are of interest, and ‘monstrous’ because of their initial crudeness and inefficiency.
market offerings may not be fully fledged swans, they must at the very least be attractive ducklings!

Having identified the phase that we are studying, we next need to make an important distinction between a technology succession and technology substitution. In a technological substitution, a new technology is used in the same way as the old technology. It is adopted because it offers a superior quality/price performance in the same basic use. The new technology has a superior performance in one or more service characteristics that are common to both it and the old technology. For example, the compact disk (CD) replaced the vinyl LP in domestic music systems in the 1980s. Consumers adopted the CD as a storage medium for music because it is more convenient (i.e. is smaller in size), requires less maintenance (no need to clean disks regularly), individual tracks can be accurately and easily selected (using a remote control unit), and is far less prone to degradation (i.e. scratches) than vinyl. Hardware manufacturers saw an opportunity to increase profits through sales of new CD players, while record companies realised that significant profits could be generated if, in addition to new material, consumers could be convinced to repurchase previously owned material, this time in the CD format.

In contrast to a technological substitution, a technological succession – the focus of this paper - opens up new consumption possibilities. These new consumption possibilities are not provided by the old technology. The new possibilities may not have been evident in the invention or innovation stages, but they certainly become apparent in the diffusion stage, as producers and consumers experiment with the new technology, possibly combining it in novel ways with other technologies that appear in this phase. One of the case studies we shall look at is the car. The car initially competed with alternative forms of urban transport (predominantly horse-drawn vehicles such as trams). Subsequently, new markets emerged as a consequence of wider social, economic and political changes. The development of suburban living after WWII saw the emergence of new type of user - the suburban car commuter.

The other characteristic of a technological succession is the entrance of new firms into the market. The shift from LPs to CDs did not change the way in which music was made, recorded, packaged or distributed. Indeed, the ‘big four’ industry labels – SonyBMG, EMI, Warner and Universal - actively promoted CD. CD did not threaten their control of the music publishing industry. Indeed, it enabled them to significantly increase their sales base and profits as consumers bought new material at higher prices on the CD format and repurchased existing titles as they replaced their LPs collections with new CD versions. This contrasts strongly with the internet. The big labels still control 70% of the world’s music market, and mainstream radio and TV airplay, but the internet has opened up new ways of recording, packaging and distributing music. Downloads, peer-to-peer file sharing, pod casting, and on-line radio stations challenge their traditional business model and their market power. March 2006 saw the first MP3-only No.1 single in the UK, bypassing the traditional distribution network completely. There has been a rejuvenation of independent labels and enabled a new generation of music entrepreneurs to enter the market, as well as the more familiar names of Napster, Rio and Apple (an established company that has used the new technology to enter this lucrative industry). Bands are also exploiting the new technology to their advantage. Artic Monkeys and Editors released self-recorded demo versions of their songs over the internet in order to build fan base in the UK and
Europe. This gave them a very strong position when it came to negotiating a contract with (independent) record labels.

2. Path dependency

Our core thesis is that successions require fundamental changes in the beliefs and actions of policy-makers, firms and consumers because these are the agents of path dependencies that maintain existing technology paradigms. A first step in understanding successions is a clear appreciation of the path dependency that maintains established paradigms. Here we consider the various sources of path dependency associated with firms (2.1), consumers (2.2) and policy makers (2.3). The discussion makes clear just how powerful these factors are and hence, why successions occur so infrequently. These factors directly affect the timing and frequency of new technology adoptions.

2.1 Supply side factors

The earliest discussions of path dependency highlighted the importance of firms in determining both the rate and direction of technological innovation. Key contributions were Atkinson and Stiglitz (1969) on localised technological improvement, the historical studies of Rosenberg (1969) and David (1975), and the work of Vernon (1966) and Abernathy and Utterback (1975) on product lifecycles. Path dependency in R&D arises because firms’ knowledge and technological expectations are built up cumulatively over time, frequently as a consequence of trial-and-error learning. In this way, firms focus on just a few potentially fruitful avenues for R&D, to the exclusion of other possibilities. The discussion was later elaborated into the idea of trajectories by Nelson and Winter (1977), Dosi (1982), and Freeman (1982). This seeks to capture the cumulative nature of the search process of firms. To a greater or lesser degree, these translated Kuhn’s (1962) theories of scientific development into the technology realm. For instance, Dosi’s concepts of ‘technological paradigms’ and ‘technological trajectories’ and ‘heuristics’ are related in the following manner:

“(T)echnologies develop along relatively ordered paths shaped by the technical properties, the problem-solving heuristics and the cumulative expertise embodied in technological paradigms... A technological trajectory is the activity of technological progress along the economic and technological trade-offs defined by a paradigm” (Dosi and Orsenigo, 1988, p.16; italics in original).

Nelson and Winter (1977) suggest that mechanisation and scaling are two key heuristics that guide firms in their search for new innovations. Through increased mechanisation, firms can reduce (expensive) labour inputs and thereby lower production costs. Scaling involves the improvement of product performance through increasing/decreasing the size of the product. For example, larger engines are more efficient than smaller engines. By contrast, the speed of microchips improves as the signal paths on circuit boards are reduced. A particularly important empirical study of trajectories is that of Sahal (1985). Using long-run data for the aircraft, tractor, and computer industries, he sought to identify stable relationships between clusters of key product features that had been scaled over time.
The nature of the artefact itself may give further direction to innovative search, leading to well-defined trajectories of incremental innovation. The work of Vernon (1966), and Abernathy and Utterback (1975) on the emergence of dominant designs is of particular importance in this respect. Contemporaneous technology battles between competing variants of a new technology product can lead to the emergence of a single, ‘dominant’ design. Through competition, market consensus is established regarding the core set of product characteristics to be produced and with which other technologies must interact (see 1.1. above). Over time, incremental innovations improve the overall quality of the dominant design, and the range of applications to which it can be applied, further enhancing the diffusion of the technology.

A far more radical version of the dominant design is the technology architecture thesis (Clark, 1985; Anderson and Tushman, 1990; Henderson and Clark, 1990; Vincenti, 1990). It is observed that technological products typically comprise a set of elements which must work together effectively. This interoperability is controlled by an ‘architecture’. An oft cited example is a computer operating system. It is argued that alternative technology variants are defined by their architectures and that these are incompatible with one another. Hence, market selection of a dominant design is in fact the selection of a particular architecture. Using this concept, Henderson and Clark (1990) derived a set of very different classification of radical and incremental innovation. According to their classification, ‘incremental innovation’ involves improvement in the performance of one or more elements of the design (e.g. an improved version of a chipset). A ‘modular’ innovation involves replacing an old technology component with another or the addition of a new technology component to improve performance (e.g. the introduction of car airbags to improve passenger safety). Importantly, a ‘pure’ modular innovation leaves the architecture unchanged. Conversely, an ‘architectural innovation’ takes the same basic set of elements (modules) and recombines them in a novel manner in order to improve performance. Finally, ‘radical’ innovation involves both architectural and modular change. Obvious examples in the computer industry, for instance, were the IBM 360 mainframe computer, the PC, and the internet. It is argued that the technology architecture thesis helps explain the highly path dependent nature of innovative search. Radical innovations are competence-destroying and so affect the underpinning knowledge of the firm (Anderson and Tushman, 1990). They also have serious organisational consequences because new ways must be found in which to assemble and optimise the production of new architecture and modules (Henderson and Clark, 1990).

### 2.2 Demand side factors

Following the work of Arthur and David, there has been much interest in demand side factors affecting path dependence. Arthur’s work on ‘lock-in’ focuses on contemporaneous technology competitions amongst competing variants of a new technology. By contrast, David’s seminal empirical study of the QWERTY keyboard (David, 1985) discusses the dynamics of sequential technology competitions – in this particular instance there was a market ‘lock-out’, with the DVORAK keyboard failing to displace the older, established QWERTY design.
At the core of this discussion is the interaction of individual choices. Path dependency arises because new adopters’ take into account the choices already made by previous adopters. Hence, an adopter’s preference (utility) function contains an autonomous individual component and an inter-personal component, such that the payoff ($\Pi$) associated with each technology variant at time $t$ is

$$\Pi_t = X_{ijt} + r (n_{jt-1})$$  \hspace{1cm} (1)$$

where $X_{ij}$ is individual $i$’s personal preference for technology $j$, and $r$ is a term that captures the increasing returns to adoption.

Strong path dependency arises when the population of adopters is relatively homogeneous with regards to the autonomous component ($X_{ij}$). If this is the case then decisions are frequency-dependent and the process reduces to a Polya urn model in which decisions depend on the relative market shares of competing technology products (Bassanini and Dosi, 1998). The properties of the Poya urn model are of interest. We know with certainty that the market will lock in to one of the competing technology variants (a winner-takes-all competition), resulting in a monopoly. However, because selection is frequency-dependent it is impossible to predict ex ante which particular variant will emerge as the winner$^2$.

The discussion complements Leibenstein’s famous 1950 paper on consumer demand. Leibenstein discussed four factors influencing the demand for a product; two of these are price factors and two are quantity factors. With regards to price, there is the conventional ‘law of demand’ with the quantity demanded inversely related to market price. By contrast, a second price effect is the ‘Veblen effect’. Veblen’s ‘Theory of the Leisure Class’ was the first to focus on the interactions between humans and artefacts in an institutional context. Artefacts are a means of communicating group membership (social status in Veblen’s discussion). The ‘Veblen effect’ manifests itself as a positive relationship between price and the quantity demanded. The effect is opposite and symmetrical to the law of demand. As with Adam Smith’s famous water-diamond paradox, the high price of diamonds makes this commodity exclusive for those that can afford it and which to distinguish themselves from those that cannot afford them. Although water is essential for life, is plentiful and cheap and, hence has no such distinction value.

On the quantity side, Leibenstein’s discussion of the ‘bandwagon effect’ foreshadows much of the work conducted in recent years. Not only did he identify the positive relationship between the attraction of a good and the number of previous adopters ($n_j$), but he also discussed the importance of bounded returns to adoption for competition. Leibenstein identifies the ‘snob effect’ as an opposite and symmetrical effect to the bandwagon effect. He posited that the desirability of a product, as a snob good, falls the more widely it is adopted because it looses its exclusivity. As we shall

$^2$ While it does not concern us directly - the focus of this paper is sequential technology competitions - there has been an important debate regarding whether markets can lock-in to an inferior quality variant in contemporaneous standards competitions. David and Arthur suggest that it is possible. This has been challenged, most notably in a series of papers by Liebowitz and Margolis (1990, 1996, 1998). They argue it cannot in the short-run or the long-run. Liebowitz and Margolis criticise the empirical data (short-run) and argue that side payments will ensure that better technology variants win out in the long-run. Hence, they argue, it is not possible to lock-in to an inferior variant.
see later, the discussion of upper bounds on increasing returns to adoption and the drive for exclusivity and distinction are important factors in sequential technology competitions.

2.3 Policy factors

Economists focus on markets with firms and consumers, and so pay less attention to the nature and extent of path dependency amongst policy-makers. In political science it is commonly assumed that the policy-maker is a ‘rational planner’ who is free to consider all feasible actions, and to take whatever course is optimal unbound by past decisions. I will argue that policy-makers need to adopt a very different position; one that explicitly recognises the path dependency of their own actions, and the role which policy itself plays in promoting or locking out new, alternative technologies.

The existence of path dependency in policy-making is fairly self-evident and (hopefully) not too controversial. Policy is the sum total of laws and regulations regarding a particular set of issues. Policy is highly cumulative. Current policy is in part the result of a long stream of decisions taken over time. For instance, tax policy is not made anew each year. Policy-makers lack the capability to enact whole new policies every year. Further, genuinely new policies (as opposed to incremental shifts in old ones) present radical dislocations. The social order can accommodate occasional radical dislocations, it cannot accommodate them every year. It is therefore for good reason that policy is highly path dependent.

Path dependency is evident in general trends that are shared by nations. It also helps to account for persistent variation between nations. Take, for example, post-war political attitudes in western Europe and the USA towards the role of the state. In the immediate aftermath of WWII, the new Keynesian consensus saw both a necessity and a role for macroeconomic intervention by the state. It also encouraged state intervention and public ownership of key sectors, such as transportation, education and health, where the quantity and/or quality of private sector provision was perceived to be inadequate. The Keynesian consensus was called into question in the 1970s and in the 1980s was overturned by a new pro-market rhetoric. Policy makers fell in love with the private sector. The upshot has been dramatic and wide ranging. First, there was the advocacy of a much reduced role for the state in macro management. In Europe this has led to the transfer of monetary control to an independent European Central Bank, something unimaginable in the Keynesian era. Second, there were calls for a smaller state. This prompted the privatisation of publicly owned firms and the outsourcing / competitive tendering of remaining basic services. Later, there was the adoption of private sector management practices (e.g. the ‘New Public Management’ movement), and more recently the promotion of public-private sector funding of large investment projects such as new hospitals, schools and other projects that would previously have been funded by public monies alone.

Within this broad and shared pattern there are national differences. These differences highlight localised path dependencies. Take health sector reforms as an example. The UK public (and the vast majority of politicians) views the publicly owned National Health Service (NHS) as a national treasure. It is, in effect, sacrosanct. Hence, no political party will consider policy measures that encourage greater private sector
involvement in health service delivery. In the Netherlands and in Germany, policy reforms will tinker with, but not overhaul, their systems of insurance funding. In the USA, the Clinton administration failed to pass legislation to revamp its medical system, by doing away with private insurance (except as a supplement) and having a federally funded system to cover all citizens regardless of employment status, income and age.

With regards to technological path dependence, political institutions themselves often play an important role in supporting and, hence, mainlining lock-in to established technologies. The car provides a clear example. The efficient running of a car-based transport system requires the co-ordination of traffic flow and parking spaces. The former includes support services such as road lighting, road maintenance, traffic signals and signs, repair garages, and break-down services. These are provided by a mix of private and public sector providers. Indeed a complicated regulation environment is present in nearly all countries, with a combination of national and local government regulatory bodies responsible for the formulation and delivery of urban and environmental planning programmes covering road construction, urban development and traffic control. Public sector institutions are additionally involved in the provision of safety-related functions such as proficiency tests for drivers, regular mechanical tests for car safety, road police, and accident and emergency services. Finally, a system of taxation operates to levy car users for these publicly provided services.

The car was actively supported by successive governments in the US and in Europe throughout the post-war era. The development of the car, rather than collective modes of transport, was viewed as the most effective means of increasing mobility (Flink, 1988). The car was a symbol of modernity, associated with notions of freedom and democracy in Europe (Mom et al., 1997) and the USA (McShane, 1994). As an icon of modernity, the car was perceived as part of a wider socio-economic change that included, amongst other things, the rise of suburban living and the relocation of branch plant manufacturing and light industry from cities to new out-of-town industrial estates. Somewhat ironically, road construction subsequently became a symbol of urban regeneration once these industries had vacated the traditional industrial districts. As the car became woven ever more finely into the fabric of society, it changed from a luxury good to a necessity.

Despite our understanding of the environmental impact of car based transport systems, path dependency makes it exceedingly difficult to change policy. On the one hand, there are real constraints on policy options. Alternatives modes of passenger transport may not readily exist in many areas. In Europe and the US, urban and suburban tram and rail networks, and inter-city rail infrastructures were destroyed in order to facilitate the development of the car. Ironically, where the privatisation of rail and bus services has occurred, there has been a further ‘rationalisation’ of the alternatives, most noticeably in rural areas but also in urban areas, leading to increased car use. Like King Canute, policy-makers are well aware of the limitations of their power, and of the political dangers inherent in setting unattainable goals. On the other hand, national and local governments are enmeshed in the effective running

3 To demonstrate the limits of his power to his subjects, the English king had his throne set on a beach. King Canute sat on the throne as the tide was coming in and famously ordered it to stop.
of a car-based transport system. This often leads to well-known ‘silos problem’. Rather than working towards a common agreed goal, some government departments (usually those charged with responsibility for car transport) will act to improve the efficacy of car transport, thereby maintaining lock-in, while others act to limit car transport and champion the alternatives.

3. Necessary conditions for a technology succession

The innovation literature discussed in section 2 contributes enormously to our appreciation of path dependency, and helps us understand why successions occur so infrequently. Nevertheless, successions do occur. Drawing on recent theoretical and empirical research, this section identifies the conditions under which a succession can occur. This further enhanced our understanding of the factors determining the timing and frequency of new technology adoptions.

As noted in the introduction, economists have traditionally ignored the presence of old paradigm path dependencies in their models. Hence, models of sequential technology competitions in the presence of path dependency are thin on the ground. Four important exceptions are the models of Shy (1996), Malerba et al. (1999), Saviotti and Pyka (2004), and Windrum and Birchenhall (2005). In addition, there are some empirical papers by Islas (1997), Yamamura et al. (2005), and myself (Windrum 2001, 2004, 2005).

Pulling this theoretical and empirical research together, we can identify a set of necessary conditions for a technology succession.

1. The functional equivalence of new and old technology products (Shy 1996; Windrum and Birchenhall, 2005). For example, the car, bus, train, tram, motorbike and bicycle are alternative types of mechanical passenger transport, each with its own particular merits in terms of journey times, cost per km, flexibility in the timing of journeys, and the pollution generated per km. Yet they all perform the same basic function – they transport a person from one geographical place to another – and so they are competing alternatives.

2. Novelty. The new technology products must offer users new consumption possibilities, previously unavailable using the old technology products (Windrum, 2005; Windrum and Birchenhall, 2005).

3. New consumer types. These new consumer types are willing and have the finances competences to experiment with, and champion, the new technology products (Malerba et al. 1999; Windrum and Birchenhall 2005).

4. These new user groups must be willing to trade-off the benefits of an established technology, e.g. those associated with a large installed base of old technology users, against the novel consumption possibilities of the new technology products (Shy 1996; Malerba et al. 1999; Windrum and Birchenhall 2005).

It is more useful to report the findings of this research rather than enter into an involved discussion of the details of the models and the empirical research.
5. New firms entering the market (Malerba et al. 1999; Windrum and Birchenhall 2005). New entrants go hand-in-hand with new consumer types in established a new technological paradigm.

6. New market entrants bring with them new conceptualisations of what the market is, and what it can become (Windrum, 2005; Windrum and Birchenhall, 2005). This is fundamentally important in the development of an alternative technology paradigm.

7. Financial capital. The availability of venture capital is a key factor affecting new industry start-ups and market entry by firms operating on other markets (Malerba et al. 1999, Saviotti and Pyka 2004).

8. The R&D response of established technology firms is a key determining factor. One response is for old technology firms to step up their R&D programmes, engage in product and process innovation, and thereby improve the quality/price performance of the old technology products. This is known as the ‘sail ship effect’. If old technology firms innovate more successfully than new technology firms, improvements in quality/price performance may be sufficient to see off the challenge posed by new technology entrants (Windrum and Birchenhall, 2005). An alternative response is for old technology producers to switch camps and set up production of new technology goods (Malerba et al. 1999). This may be an attractive proposition for firms with relatively small market shares in the old technology industry. Like new start-up firms, they may view the new technology as an opportunity to be become a major industry player. The ability to successfully switch strongly depends on the transferability of knowledge and competences from the old to the new technology (Gort and Klepper, 1982; Anderson and Tushman, 1990; Malerba et al. 1999). Finally, it may be a dominant old technology firm that develops and launches the new technology. While this is less common, the notable example was IBM’s championing of the personal computer as a serious business machine. The development and launch of the IBM PC gave it credibility amongst the business community, and became the dominant design.

9. New policy models. The development of a new technology paradigm requires the development of a ‘new policy model’. At the core of the new policy model is an alternative ‘mentality’ of policy practice (Foucault, 1972). This translates into a relatively coherent, explicit cluster of policy positions and practical measures. Old models and mentalities are embedded in institutional structures and arrangements, and can persist long after the technologies which they originally supported have disappeared. Hence, a new policy model must displace the old policy model if a new technology paradigm is to develop.

10. The most visible (and readily quantifiable) aspects of a succession are new product designs and new process technologies (Shy 1996; Islas 1997; Malerba et al. 1999; Saviotti and Pyka 2004; Windrum and Birchenhall 2005; Yamamura et al. 2005; Windrum 2005).

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5 The term was first coined by Gilfillan (1935) when referring to the rapid spurt of technical improvement in sailing ships that followed the introduction of steamships in the 1860s.
11. Timing. The probability of a succession occurring may differ at different moments in time, with distinct ‘windows of opportunity’ arising.

Let us investigate in more detail the time related conditions of technology successions. This has not been addressed in the literature on sequential technology competitions, and is important for effective policy formulation.

- **Investment and innovation cycles**

The probability of a succession occurring may be affected by investment cycles, economic cycles, and patent cycles. Some industries have distinct investment cycles tied to the scrapping of existing product vintages. For instance, the investment cycle in the computer industry has a periodicity of around 3 years, offering new entrants a distinct window of opportunity to launching alternative, new technologies. Discussion of the link between macroeconomic cycles and the introduction of new technologies dates back to work of Mensch (1979) and Freeman *et al.* (1982). Empirical evidence indicates that initial investments in new technologies are more likely to occur at the top of the economic cycle, when the investment climate is favourable and venture capital more readily available, that at the bottom of the economic cycle. Patents play an important role in the R&D strategies of pharmaceutical firms and in certain manufacturing industries. Patents not only cover existing product technologies but also prospective, alternative technologies. It is not uncommon for dominant (old technology) firms to engage in defensive patenting. Dominant firms take out patents on core aspects of new technologies, not in order to produce these themselves but to deny access to potential new rivals, thereby protecting their established technology products and the profits generated by these old technologies. The R&D activities of new technology entrants are unrestricted once such patents have elapsed.

- **Generation-based cycles**

Distinct windows of opportunity exist on the demand side that can give rise to regular cycles. These may be linked to generations and be very frequent, as in the fashion and music industries. Each generation of teenagers seeks to distinguish itself from its parents and, just as importantly, the previous teenage cohort (older bothers and sisters). This gives rise to well-documented cycles of teenage clothing and music fashions, which occur every 3 to 4 years. Other demand side cycles, with longer periodicity, are linked to the product lifecycle. As Leibenstein (1950) observed long ago, highly successful products eventually saturate markets and upper limits exist on the potential network externalities. What is more, when a product becomes widely diffused, it loses its exclusivity – it is no longer ‘hip’ and loses its appeal (i.e. it has a zero snob effect). As marketers are well aware, consumers are potentially very interested in the next new product to come along. This is because the new product has a strong snob effect - kudos is attached to the new technology product because ownership differentiates and sets apart early adopters from the rest (who are still using the old technology product). In a very real sense, the success of an established technology breeds its own destruction.
Supply side cycles

There are additional supply side aspects of the product lifecycle that can give rise to windows of opportunity and, hence, cycles. Technology trajectories eventually run into decreasing returns as technological opportunities are exhausted. Notably, there are upper limits to scaling and mechanisation. ‘Wolff’s Law’ states that physical limits impose boundaries on the gains that can be achieved through scaling (Mensch, 1979). For instance, quantum mechanics imposes a physical limit on the ability of microchip manufacturers to increase chip speed through miniaturisation. Sahal (1985) additionally observes that limits to scaling arise from the non-linearities that exist between the interdependent components that make up a product. A design can work effectively within a range of scale values but beyond a certain threshold, further changes in size require changes to be made to both the form and structure of a product. Sahal illustrates his argument using the piston propeller airplane engine. Scaling of the piston engine was limited by increasing vibration and by the tips of propellers, which became increasingly inefficient as one approached the speed of sound. It was this physical limit that led aeronautical engineers to consider R&D into new, alternative engine designs.

In addition to limits on performance improvements achievable through scaling, there are limits to gains in production costs available through increasing scale. Upper bounds on scale economies are well discussed in economics, and are associated with physical limitations and with the loss of managerial control of the production process as scale increases. This opens a window of opportunity for the adoption of technologies that improve the organisation and managerial control of production. There may also be longer-run cycles associated with fundamental shifts from old to new production paradigms. Hölzl et al. (2006) discuss the switch from Fordist to Post-Fordist technologies. Fordist mass production technologies enabled firms to modularise production activities, and at the same time centralise management and R&D in order to increase control over production and product development processes. Post-Fordist technologies make a decentralised and externally modularised architecture possible. Where Fordist paradigm focused on reducing the costs of internal coordination, the Post-Fordist paradigm focuses on reducing costs of external coordination, facilitating greater internetworking of firms along the supply chain.

The core concepts of Post-Fordism are lean production and just-in-time delivery. Herein lies the importance of new internet technologies. They enable an effective flow through of information. Through a modularisation and reintegration of their activities, producers can accommodate ongoing improvements in component design by other firms without the need for changes elsewhere. This opens up the potential for product innovation along the supply chain, while simultaneously enabling firms to offer a broader range of designs to the end consumer. Greater customisation is possible, as is the ability to respond to changes in demand for different features. Finally, there are huge savings in component inventories. The net result is large efficiency gains through a reorganisation of external relationships. This new paradigm, supported by internet-based technologies that facilitate reconfigurations in firms’ organisational architectures, enables the integration and monitoring of production processes that are external to the firm.
Conditions 1 – 11 involve fundamental discontinuities amongst the three sets of agents: consumers, firms, and policy-makers. These must all occur in order for a technology succession to be possible.

4. Commercial strategies for successions

We have discussed the necessary conditions for a succession that have been identified by the literature. Let us now examine the strategies that private sector firms have used in order to win sequential technology competitions. As we shall see, new technology entrants cleverly set up the necessary conditions for a succession, while simultaneously exploiting opportunities associated with weaknesses of old technology firms and products. It is important for policy makers to understand these strategies and when they are most effectively played.

4.1 Demand-side strategies

Case studies indicate that new market entrants can successfully employ a number of strategies to overcome the large installed user base enjoyed by established firms.

• To start with, the new entrant could technically differentiate its product so that it is incompatible with the old technology (for example, CD’s not being compatible with LP’s). This clearly sets up a winner-takes-all competition in the minds of consumers. Alternatively, the new entrant can design its technology as a complement rather than a full substitute to the dominant technology as to profit from the already large installed base (for example, nineteenth century steam ships used for inland shipping being complementary to sailing ships used at sea).

• Having done this, success lies in understanding the nature of consumer demand and formulating appropriate strategies. Consumer demand is invariably heterogeneous and subject to change, providing late technology entrants the opportunity to overturn established firms with large installed user bases. This is true even when there is a well-established dominant design and a market is dominated by a few large firms.

• Successful strategy depends on identifying and developing new user types interested in pursuing the alternative consumption possibilities that are facilitated by the new technology. This is an important point. Users are interested in the new consumption possibilities, not in the technical features of the technology per se. The strategy is therefore to identify and support new user types who wish to differentiate themselves through the consumption of new products. As noted previously, there may be a new generation of users or else an existing set of users may wish to set themselves apart through the development of new consumption patterns (the snob effect).

• Heterogeneity may mean there is latent demand amongst dissatisfied users of a dominant design. A good example is provided by the camera industry (Windrum 2005). This comprises two distinct types of amateur user: the occasional user, and
the serious hobbyist. Both were being sold the same dominant design, the viewfinder camera, in the 1950s. The introduction of the two radically new camera designs, the single lens reflex and the 126 enabled new entrants to take over the market, which split into two clear segments. The basis for their success was the recognition of latent, unsatisfied demand and the identification of designs with more attractive consumption possibilities for two distinct types of consumer.

- Another strategy is to build up a core following in a trend-setting group which other groups aspire to, rather than trying to win over all consumer types. This strategy is frequently linked to a branding strategy that targets leading magazines and other media to quickly build brand awareness amongst the wider public.

- A well-established marketing strategy is the short-term price offer / ‘give away’. Here users familiar with an established product are encouraged to try out the new alternative. This can be an effective way of quickly building an installed user base, and is popular with companies seeking to gain a rapid internet presence.

- Finally, the cross-leveraging of installed user bases is a strategy that can be played by existing industry firms with a large installed user base in a related industry market (Windrum 2004). This late entry strategy that has been very successfully used by Microsoft. By linking the browser market (where it was weak) and the operating system market (where it was strong) it was able to leverage its installed base of Windows and Office across to the browser market and thereby gain control of this market as well. More recently, it successfully used the same strategy in the media player market.

4.2 Supply-side strategies

Case studies have also identified a number of supply side strategies that have been used by new market entrants to overcome the large installed user base of an established firm.

- New entrants can enter mature markets by engaging in radical product innovation. Through radical innovation, late Japanese entrants successfully entered a series mature manufacturing industries in the 1960s and 1970s, such as cameras, hifi and motorbikes (Windrum 2005; Yamamura et al. 2005).

- Radical process innovation is another means of entering a mature industry. For instance, Pilkington’s invention of the float glass process is an example of a radical process innovation that enabled a late firm entrant to dominate large scale glass production (Uusitalo 1995; 1997). A key element in the success of late Japanese entrants in the car, motorbike and electronic industries was the development of lean production and just-in-time delivery (Windrum and Birchenhall 2005).

- A strategic factor discussed by Porter (1985) is better/improved access to key local/national resources, i.e. wages and other input cost advantages.
A new entrant may have new organisational structures that more effectively manage internal and external resources. Organisational innovation is the means by which firms can reorganise their hierarchical structures, internal procedures, and external relationships along the supply chain (Hölzl et al. 2006).

Building alternative/superior distribution channels is an important strategic objective. A key aspect of Microsoft’s victory in the browser war was its exploiting its strength, and Netscape’s weakness, in the traditional and new distribution channels for browsers, i.e. PC manufacturers and internet service providers (ISPs) (Windrum, 2005).

The formation of strategic alliances is another key strategy (Pyka and Windrum 2003). This can take the form of open licence agreements between firms that produce the same product. Here R&D efforts are shared, through the purchase of a licence, by all firms wishing to produce the technology. The key potential advantage of this strategy is the ability to quickly build a critical mass of producers, all of whom are committed to backing and developing the technology. This was the strategy used in the development of the IBM PC.

An alternative basis for a strategic alliance is the production of complementary goods. In contrast to the open licence strategy between producers of the same product, here the alliance is between producers of goods that complement one another. This not only requires the purposeful design of interoperability between the set of complementary goods, but also the creation and management of linkages between their respective competences and knowledge bases. This entails an understanding of what partners can reasonably expect of each other (their relative strengths and weaknesses) and how partners’ competences can be synthesised together to create an innovative product (Pyka and Windrum 2003).

5. A co-evolutionary policy framework

Having identified necessary conditions for successions and strategies used by firms to bring them about, let us move on to consider the role of policy makers and policy options that encourage the diffusion of more environmentally friendly technologies.

To start with, we need to flesh out and develop the notion of the policy maker being one of the key agents that make up a complex selection environment. In the framework that I shall put forward there are 3 types of interacting agent: firms, consumers and political policy makers. The technology beliefs and actions of each type of agent are shaped over time by the beliefs and actions of the other agents. This interaction establishes what I have elsewhere called ‘co-evolutionary learning’.

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6 In Windrum (1999) and Windrum and Birchenhall (2005), market interactions were assumed to take place within a given regulatory and societal environment, enabling the discussion to be limited to consumers and firms. Here that simplifying assumption is relaxed and the political policy maker is endogenised within the framework.
Co-evolutionary learning has two aspects. First, technology products are the objects via which different sets of agents communicate their expectations, mentalities, desires and competences. Technological change is the consequence of inter-agent learning. Rather than being an independent causal factor, a product is a mediation device. One cannot understand the emergence and use of a technology without an explicit examination of the way in which the (possibly conflicting) interests of different agents interact through a product. It is this inter-agent mediation that leads to technological change. The features of technologies change and substitutions occur as consumers, firms and policy makers interactively learn about the new possibilities associated with the production, consumption and environmental impacts of new technologies.

The second aspect of co-evolutionary learning is that feedbacks between agents also change the beliefs and actions of firms, consumers and policy makers over time. As discussed in section 3, successions require radical changes to occur in the mentalities, behaviours, and actions of agents. A succession involves far more than the substitution of one set of technology products with another. It involves the displacement of existing consumer preferences by new consumer classes with alternative preference sets, the displacement of established market firms and production structures by new firms with new production structures, and old policy regimes with new policy regimes. In sum, it is a gestalt shift. It is the replacement of one paradigm of mentalities, behaviours and actions with a new paradigm (Figure 1). This radical shift is what Schumpeter’s describes in his ‘gales of creative destruction’. It is widespread in reach, and deep in impact.

![Figure 1. Co-evolutionary learning mediated by changing technologies](image-url)
This co-evolutionary framework captures three spheres that shape environmental policy: the business sphere dominated by market relationships between customers and suppliers, the regulatory sphere of national and local government, and the wider societal sphere in which public opinion about issues are influenced by consumer organisations, environmental groups, the media, public opinion leaders and independent scientists.

5.1 Case studies

In order to develop the framework, section 5.1 considers two case studies: the evolution of car based transport (5.1.1) and the evolution of refrigerants (5.2.2). The case studies provide a set of initial stylised facts that we wish to capture in the framework, and a set of outcomes we would expect the framework to reproduce (as an initial validation check). Section 5.2 develops the co-evolutionary framework by formalising the behaviours, actions, and interactions of our three agents: policy makers (5.2.1), consumers (5.2.2), and firms (5.2.3).

5.1.1. Case studies: the evolution of car based transport and the evolution of refrigerants

The actions of policy makers with respect to the car are particularly interesting. The modern industrial city was a 19th century phenomenon. Steam power enabled the relocation of manufacturing towards cities, where most consumers lived and where labour could be found. Relocation in turn made it even more attractive for the population to relocate from the countryside and there was a dramatic growth of cities in Europe and the USA. This growth was accompanied by health and hygiene problems. Swelling urban populations produced unprecedented densities of horse and human excrement, much of which found its way on to public streets. Since the middle ages in Europe, epidemics and diseases such as cholera, malaria, and tuberculosis were linked to ‘miasmas’ – a poisonous vapour created by decaying organic material. In the 19th century, health theorists morphed the notion. Using their knowledge of the respiratory process, they “placed the blame on exhaled carbon dioxide in unventilated rooms and sewer gas, an often colorless, odorless gas given off by inadequately flushed plumbing or poorly cleaned privies” (McShane 1994, p. 24). The solution was proper ventilation to remove these gases. This gave rise a ‘public hygiene movement’. The movement led to a seismic shift in public opinion, to fundamental changes in urban living, and impacted on the nature of politics itself. Modern local (civic) politics was born in this era. This started with an expansion of street cleaning departments and the construction of publicly funded sewers and water systems for clean drinking water. This required the levying of local taxes to pay for this infrastructure and the development of municipal departments to construct and maintain it. The development of new municipal organisations necessitated an amendment of the liberal political tradition of upholding the rights of the individual. In the UK, for example, intervention was legitimated by the new Benthamite utilitarian philosophy of ‘bringing the greatest benefit to the greatest number’.

Local government also began to take responsibility of the urban street away from individual citizens. Residents had been individually responsible for the area of road in front of their houses. This responsibility was taken over by local government. Raised
pavements were constructed. This separated pedestrians from horse traffic and their excrement, leading to improvements in road safety and hygiene. City planning departments were created, charged with the responsibility of changing the urban city itself in order to reduce disease and improve health. In Europe and the USA, the target was densely packed, ill ventilated row houses that were inhabited by the city working classes. Other social groups viewed these as the source of a moral and social ill health, as well as physical ill health. The new city planners removed these tenements and worked with private sector firms to open up spaces and let in ‘healthy’ light and air in the rebuild. The astounding transformation of Paris provided the template: a sprawling mass of dense and poorly constructed housing being replaced with grand avenues and public parks (the lungs of the city).

It was in this new urban environment, at the constellation of social, economic and political attitudes, that the car was born. The public hygiene movement had led to the removal of human excrement from the street. The one remaining source of organic pollution was the horse. As discussed previously, the pollution associated with horses was well understood by the end of the 19th century, the pollution associated with cars was not. There was another factor favouring the car. This was the desire for the new concept of ‘suburban living’. The concept was a child of the public health movement. Suburban living was both the moral and physical healthy alternative to the city.

In the medieval European city, suburbs (which literally mean homes under defensive city walls) had been prohibited or at least heavily discouraged because they could give shelter to an attacking army. With urban land within the city walls at a premium, there was little physical space for the rich to segregate themselves from the poor. Interestingly, the pattern of segregation that did exist within the city walls was the opposite of the modern city. Because transportation was primitive and most people walked to work, city centre residences commanded higher prices. Relatively poorer people tended to reside on the more remote outskirts. This pattern is still recognisable in the 17th and 18th century buildings of Amsterdam. Areas close to the old city wall, such as Mokum, were the dwelling of the city poor while the rich lived around along the central portions of the grand canals, well within the city walls.

The pattern had started to change in the 18th century as horse pulled carriages and wagons improved. The important change came with the introduction of the railroads and the electric tram (streetcar). The railways enabled the upper classes to relocate to the countryside and city to commute to work on a daily basis. The electric tram enabled the middle classes to relocate to newly built suburbs from the 1890s. Travel by tram was much faster than by horse and, unlike train travel, daily tram travel was affordable for the middle classes. The maximum speed of an electric tram was 12 mph compared to 4mph or a horse drawn omnibus. The increase in speed translated into a significant expansion of the radius of land accessible for settlement, from 12.26 square miles with the horse drawn omnibus to 113.86 miles with the electric tram (Bass Warner Jr., 1973). In practice, the desire for suburban living remained an unsatisfied ‘new taste’ until the advent of the car. By the 1930s the car had become the dominant form of urban travel in the USA, while in Western Europe the transition occurred shortly after WWII. There was the emergence of new type of commuter: the suburban car commuter.
This highlights two important issues in technology successions. The first is the role played by *intermediate technologies*. The pollution and congestion created by horse based transportation provided a ‘window of opportunity’ for new transportation technologies. It was the electric tram, not the car, which started to displace the horse as a means of mass urban transport. While the electric tram would later be displaced by the car (and in this sense came to represent an ‘intermediate’ technology), it played an essential role in a wider transformation process of the city (Nye 1990).

First, it was the diffusion of the electric tram which resulted in the disappearance of the horse drawn omnibus. Horses remained in certain niches - private taxis, freight transport, and in the countryside where electric power line were too expensive to erect given low population densities. Second, as noted already, it was the electric tram which enabled suburban living to be explored for the first time. Due to relatively low fares and its greater speed, the electric tram made it possible for the middle classes to live in suburban communities, far from the city centre. Third, the electric tram assisted the transformation of the city centre itself. The upper and middle classes may have vacated the city centre as a place of residency but they continued to use it as a centre for business and entertainment activity. The city centre transformed into the ‘central business district’ we know today, with a concentration of business and entertainment activities such as department stores, theatres, museums and cinemas. Fourth, electric trams were a key factor in the reconfiguring of the street. In the medieval city, the street was a place for social interactions, for public gatherings, and for trade. This had started to change in the horse era. Parks became the setting for public gatherings and trade was removed from the street and conducted in high street and corner shops. Yet, prior to the 1890s, many streets still fulfilled their function as a social meeting place. Now, as the upper and middle classes started to relocate, the street was increasingly defined as a transport artery which needed to be kept clear in order to ensure the free flow of traffic (McShane 1994). Fifth, the electric tram further enhanced the idea of high speed transport. This had first been introduced by the advent of train travel between cities. Now the notion of high speed was being applied to travel within the city (Nye 1990; McShane 1994).

This leads us to another key concept, that of *deep path dependency* across paradigms. Successions involve new technologies that in some way do something different to the old technologies that they displace. At the same time, the new technologies share certain features of the old technologies. Successions involve a sequences of technologies that unfold, one form another. Each succession contains elements of continuity and change. This trans-paradigm or ‘deep’ path dependency can manifest itself in numerous ways. First, there is *conceptual innovation*. The concept of the street – its meaning and its uses – was in part reorganised and reinvented by the electric tram. This was subsequently further reorganised and reinvented by the car.

With regards to conceptual understandings about what new technologies are and what they can do, these are often framed by the preceding technologies. For instance, the terms used with technologies often refer to a prior technology because these were a convenient means of conveying the meaning of the new technology to the first generation of new adopters. Take the car. The concept of private (individual) automated passenger transport was radically new. Yet the concept of what a car ‘is’ was conveyed in its original name of the ‘horseless carriage’. What is more, the power of a car engine was (and still are) measured in ‘horse power’. The PC was another
radical innovation. It broke with the previous technology of a central mainframe processor, operated by specialist staff, connected to users who operated dumb display terminals. Yet the very term ‘personal computer’, also known as the ‘desktop’, conveyed the idea that this is a small, stand alone version of the mainframe designed to fit on one’s desk. The aeroplane displaced the ship as the primary means of mass passenger ocean transport. It is a radically different technology and means of physical travel. However, consumers of flight travel could readily understand that the ‘aircraft’ is ‘piloted’ by a ‘captain’ and his ‘cabin crew’. As ‘passengers’, they ‘stow’ their luggage when they arrive ‘onboard’ and are served in-flight meals by air ‘stewards’ and ‘stewardesses’. Commercial aeroplane firms deliberately adopted terms and concepts used in luxury ocean liner travel in order to make this radically new technology more familiar. The transference of terms and ideas assist users in the cognitive transition from one technology to another.

One also finds this combination of change and continuity in the technical features of new technologies, i.e. as well as containing the novel technical elements which define them they retain elements of the previous technology. Thus the electric tram was a motorised version of the horse drawn omnibus. It was still a public transport vehicle, but it facilitated the movement of the middle classes to the suburbs, where began to engage in private technology consumption. This paved the way for the car. The earliest cars were indeed carriages (often built by stagecoach firms) powered by an engine rather than a horse. But they were a private transport vehicle; one that would enable the middle classes to really engage in and develop a distinct, suburban lifestyle.

Here, then, is the core understanding of technology successions. They involve the unfolding of new technological trajectories from old trajectories as sequences of new products alter technology space, thereby facilitating the evolution of different consumption opportunities and lifestyles over time. It was not the technical features of the car per se that led to its rapid adoption. It was the demand for suburban living, a concept first explored in the era of the electric tram, that drove its rapid diffusion after WWII. Cars enabled the middle class to truly explore the new set of consumption opportunities of suburban living. What is more, the car was championed and popularised by the media and by policy makers. The media, particularly Hollywood and US consumer product advertisers forcefully shaped the identity of ‘modern suburban living’, perhaps most distinctively in the new consumption-based lifestyle imagery of the 1950s ‘American Dream’. This was reinforced by the active support of successive governments in the US and Europe throughout the post-war era. The development of the car, rather than collective (public) modes of transport, was viewed as the most effective means of increasing mobility. The car was a powerful symbol of ‘modernity’, associated with notions of freedom and democracy, to be championed in the Cold War. As the car-based suburban living became woven ever more finely into the fabric of western society, so car ownership became a basic necessity.

Policy makers and political institutions at all levels (local, regional and national), became enmeshed in the effective running of the mass car transport system. The efficient running of a car-based transport system requires the co-ordination of traffic flow and parking spaces. The former includes support services such as road lighting, road maintenance, traffic signals and signs, repair garages, and break-down services. These are provided by a mix of private and public sector providers. Indeed a
complicated regulation system is present in nearly all countries, with a combination of national and local government regulatory bodies responsible for the formulation and delivery of urban and environmental planning programmes covering road construction, urban development and traffic control. Public bodies are additionally involved in the provision of safety-related functions such as proficiency tests for drivers, regular mechanical tests for car safety, road police, and accident and emergency services. Finally, a system of taxation operates to levy car users for these publicly provided goods.

In Europe and the USA, the image of the car changed as the negative environmental impact of intensive car use became apparent in the 1970s and 1980s. But rather than supporting moves to jettison the car, public opinion in these countries views the car as a ‘necessary evil’. Rather than championing alternative technologies, policy makers are currently supporting established vehicle manufacturers and oil companies in their attempts to find ‘technology fixes’ for the worst excesses of the car, thereby ‘greening’ the existing car-based transport paradigm. A series of incremental innovations have been made to the car engine since the 1970s, such as catalytic converters, lead-free petrol, electronic engine monitoring systems to improve emissions from petrol engines, and most recently the launch of hybrid petrol-electric battery cars (e.g. the Toyota Prius).

5.1.2. Case studies: the evolution of car based transport and the evolution of refrigerants

In contrast to the car, policy makers have actively targeted refrigerants as a means of reducing greenhouse gas emissions. In part, this no doubt reflects the fact that it is easier to implement policy in this area. There are a handful of chemical firms that produce refrigerants and the key adopters are supermarkets and manufacturers of refrigerators rather than individual households. The business-to-business refrigerant market is thus divided into 2 parts: low temperature applications (freezers) and medium temperature applications (fridges). In terms of volume, supermarkets (low temperature applications) are by far the largest users. The initial draft of the first Montreal Protocol agreement in 1987 did not call for a full phasing out of chlorofluorocarbons (CFCs) but this changed in light of new scientific evidence. EU legislation was already one step ahead of the Montreal Protocol in this respect, and since 1987 has consistently introduced tighter phase out schedules (Landis Gabel 1995; Glynn 2002).

In this technically complicated area, opinion has been shaped by scientists, specialist parts of the media, and by activist groups such as Greenpeace rather than by the general public. Policy makers have been quick to respond to shifts in opinion – and there have been a few! First, there was the shift against CFCs. The problem was that there was not an immediate alternative to hand. This was reflected in the 1990 Protocol, which did not legislate in favour of an alternative but simply established dates for the phase out of CFCs. It was left to chemical manufacturers to identify an alternative. Their first response was hydrochlorofluorocarbons (HCFCs). HCFCs were yet another example of a quick ‘technology fix’ intended to maintain an existing technological trajectory. These had actually been produced since the 1930s and so chemical manufacturers did not need to engage in radical R&D effort. The key selling
point of HCFCs to supermarkets and refrigerator manufacturers was that it was a direct substitute that did not require alterations to existing machinery. This meant that early adopters could be seen to be showing concern and making a positive environmental statement. Unfortunately, while HCFCs are less damaging than CFCs, they also contain chlorine, the active ozone depleting agent. This was highlighted by scientists, the specialist media, and by Greenpeace who actively targeted the largest supermarkets with a campaign to stop the use of HCFCs. In 1992 the second Montreal Protocol agreement was amended to include HCFCs as well as CFCs, setting phase out dates for HCFCs of 99.5% by 2020 and 100% by 2030.

The next option put forward by chemical manufacturers was hydrofluorocarbons (HFCs). As the name indicates, HFCs do not contain chlorine and so are not ozone depleting. Unlike HCFC, HFC was a new chemical with no previous history of use. The first HFC was first launched by ICI, who began production of HFC-134a in late 1990. This could be used in medium temperature applications only. Later, Du Pont introduced HFC-404A which could be used in both low and medium temperature applications (Glynn 2002).

A key advantage of HFCs, as far as supermarkets and refrigerator manufacturers were concerned, was that they did not require the replacement of existing refrigeration systems or of existing practices. Hence, following the definition given in section 2, HFCs were an incremental innovation. The one problem that new HFCs posed was their incompatibility with traditional lubricants. Chemical firms developed a new set of lubricants, though there were some initial teething problems. Still, a technology fix seemed to have been found and there was a rapid take up of HFCs. There was a real expectation on the part of chemical manufactures that, having been set a clear task by the new legislation, a solution to the CFC problem had been found. Unfortunately for them, opinion (and policy) shifted yet again in the mid-1990s. The scientific community and activist organisations successfully pushed for a change in focus. There was a shift from a narrow focus on ozone depleting chemicals to a wider consideration of global warming due to total CO2 emissions. A key event was the introduction of the new concept of ‘total equivalent warming impact’ (TEWI). This replaced the previous standard indicator, the ozone depleting potential (ODP) of chemical CFC substitute. As noted, HFCs have a zero ODP because they do not contain chlorine.

TEWI came out of two studies that were jointly funded by the US Department of Environment and the Alternative fluorocarbons Environmental Acceptability Study (AFEAS). TEWI comprises two parts. One is a measure of the ‘direct’ global warming potential (GWP) of a chemical. This is determined by the extent to which molecules scatter infra red radiation, thereby affecting the ability of the ozone layer to repel harmful rays. The other part is a measure of the ‘indirect’ contribution of energy consumption to CO2 emissions. The adoption of TEWI was by policy makers marked a policy gestalt shift. From now on the debate was no longer just about chemical refrigerants but the energy consumption of refrigerator systems. The clear message of TEWI is that the main contributor to global warming is the indirect effect associated with energy consumption. The shift was enacted in the 1997 Kyoto Protocol that was signed by 171 nations. Despite the opposition of the chemical industry, the Kyoto Protocol included HFCs along with other greenhouse gases. Prior to this, the Danish government has already announced it would unilaterally phase out HFCs.
Glynn (2002) discusses the challenge faced established chemical manufacturers by a strategic alliance of new market entrants at the turn of the century. Whereas the established chemical firms continued to back HFCs, the new entrants championed hydrocarbons (HCs). This directly challenged the established chemical oligopoly. This new strategic alliance comprised Greenpeace, DKK Scharfenstein, and a number of manufactures of hydrocarbons (HCs), such as Calor in the UK. These were not new start-up firms but an existing set of organisations with strategic strengths in HC technology, marketing and distribution, and the political lobbying of governments and supermarkets. Greenpeace worked with DKK Scharfenstein (Germany) to develop a new refrigerator technology called ‘Greenfreeze’. It was successful in getting a number of prominent UK supermarkets, such as Tesco and Iceland, to purchase HC refrigerators for a number of new supermarket sites. It also persuaded the UK Department of Environment to purchase a number of its refrigerators for research purposes in 1993. The key technical problem was to obtain sufficient supplies of HC refrigerants, given the chemical industry was opposed to HCs. This led Greenpeace to collaborate with firms from other industries. In the UK, for instance it established a relationship with Calor. Calor is the largest supplier of LPG in the UK and already had significant expertise in HC technology, which it had already used to help the aerosol industry move away from CFCs. Further, Calor had international marketing expertise and a global distribution network.

The chemical manufacturers and this new strategic alliance made a series of claims and counter claims regarding the relative merits of HFCs and HCs. Greenpeace and Calor highlighted the fact that HCs have a zero GWP, because they break down into their natural components before reaching the ozone layer, while HFCs have a high GWP. HCs can be used with traditional lubricants and, more importantly, require a significantly smaller refrigerant charge. This means they are in principle more energy saving than HFCs, with a lower TEWI and greater cost savings for adopters (ENDS Report 248, 1995). Yet, while Greenpeace and Calor made inroads with the supermarkets, they had problems selling to refrigerator manufacturers. According to Calor, it is unable to break an alliance between the chemical companies, compressor manufacturers and the refrigerator manufactures that has built up over 50 years and which is led by the chemical companies (Glynn 2002).

The chemical and refrigerator manufacturers responded to the HC challenge in two ways. First, they highlighted the safety concerns associated with HC refrigerants. HCs are highly flammable and care in needed in their handling. Calor acted to counteract this tactic. In the UK, Calor successfully pushed for the national certification of service engineers handling HCs, and developed the training programmes. It did not succeed in the US, however. Fears of litigation prevented HC technology from establishing itself in the US. The second tactic was the introduction of new HCFC refrigerator designs that were not only more energy efficient but which significantly reduced leakage rates. Given that leakage rates of old systems were around 30%, the impact on TEWI and on users’ energy bills was significant. This enabled the HFC manufacturers to claim that, despite having a high GWP, HFC refrigerators are more energy efficient than HC refrigerators and so have overall have a lower TEWI. This is disputed by Greenpeace and Calor.
At the time of writing it seems that the established industry players are seeing off the hydrocarbon challenge. Part of this success lies in the new R&D effort along the fluorocarbon trajectory. Indeed, it is an excellent example of the sail ship effect discussed in section 3. The threat posed by the combination of new legislation and a new set of market entrants promoting an alternative technology, prompted new R&D by the established chemical and refrigerator manufacturers along the existing technology trajectory. Part of the success lies in the continuing control of the distribution channels by the chemical and refrigerator manufacturers, and the close relationships they have built up with supermarkets over the previous 50 years. As discussed in section 3, the reaction of the established players is important. If a number of these were to switch to support hydrocarbon technology then the situation would change. As it stands, they are maintaining the old the fluorocarbon trajectory. Finally, there is the timing of the HC challenge. The supermarket investment cycle in refrigeration is long – around 15 years. Hence most investments are associated with the opening of new supermarket sites. Glynn (2002) suggests that the HC challenge was 3 to 4 years too late. With the writing on the wall for CFCs, supermarkets had already started to invest in the fluorocarbon replacements – first HFCFs and then HFCs – into their new sites before the HC option became available. Following the discussion of investment cycles in section 3, there will not be another window of opportunity for at least another decade unless something dramatic changes.

5.1 Formalising the co-evolutionary framework

5.1.1 Policy maker

It is traditional for political scientists to model the policy maker as a rational and strategic actor who wishes to be elected and subsequently re-elected in the future. Policy is the means of securing (re)election. For each policy there is assumed to be a distribution of voters’ opinions on a particular issue. The policy-maker therefore seeks to identify the opinion of the median voter, as this maximises the probability of (re)election. In order to capture the dynamics of technological change, this model must be altered. Like firms and consumers, policy-makers are boundedly rational agents that are engaged in the open-ended search of dynamically changing environments. This is due to two factors. First, the interaction between agents means policy-makers not only face problems in collecting and processing information, they must also deal with the algorithmic complexity of the non-linear interactions and their ability to define preferences over expected actions, events, and outcomes. The policy-maker is not initially endowed with an understanding of the underlying structure of the environment in which (s)he operates but must develop, through experience, a representation of the underlying structure. Second, radical innovation involves the introduction of new technological objects into the environment that alters the underlying structure and, hence, the payoffs associated with alternative policy actions. Agents operate in the presence of Knightian uncertainty: they cannot know, \textit{ex ante}, the outcomes of a particular course of action (Knight 1921). This is why successions require policy-makers to develop fundamentally new policy mentalities. Radically new behaviour and action on the part of firms and consumers means old policies will no longer work. Policy makers are required to develop new mental models.
This appears to lead us to a problem. On the one hand, it is suggested that radical technological change leads to a change in the mental models of boundedly rational policy makers. On the other, it has been found that the development of new mental models by policy agents is a prerequisite for a succession occurring (section 3 above). So how is this chicken and egg circularity to be broken? There are a number of different possible avenues. Let us here consider a boundedly rational policy maker whose objective is seeking future re-election \((\text{elect}_{t+1})\). The likelihood of re-election is a function of the outcome of past elections \((\text{elect}_t)\) and current policy \((\text{pol}_t)\).

\[
\text{elect}_{t+1} = f(\text{elect}_t, \text{pol}_t) \quad (2)
\]

The outcomes of past elections are given, so the control variable that maximises this objective function is current policy \((\text{pol}_t)\). Current policy itself comprises two components, previous policy decisions \((\text{pol}_{t-1})\) and current public opinion about key issues \((\text{opin}_t)\).

\[
\text{pol}_t = f(\text{pol}_{t-1}, \text{opin}_t) \quad (3)
\]

Linking up with the discussion in section 2.3, the variable \(\text{pol}_{t-1}\) introduces a strong element of path dependency in current policy making and available options. There may be good reasons for inertia and path dependency. First, policy changes impose real administrative and technology costs on the policy maker. Second, changes impose social costs on individuals, and the rational policy is aware of this and will take this into account.

The second component \(\text{opin}_t\), is a factor for change. Politicians are sensitive to large swings in public opinion on key issues. Public opinion is a very hard phenomenon to measure, let alone model. In terms of environmental policy, an important link does exist between technology use and public concern regarding its environmental impact. We have seen governments make rapid policy changes in response to concerns about pollution (McShane 1994; Grübler 1998; Glynn 2002; Flannery 2006).

Threshold effects often exist. Initially, the pollution generated by a particular technology tends to go unrecognised, only making its presence felt in the later stages of diffusion when a large number of adopters are using the technology. For instance, threshold effects existed for the burning of coal fires and the health problems associated with city smogs, and for the use of petrol engine cars and their associated health and environmental problems. Indeed, in the early days of the car it was perceived as a healthy alternative to horse transport. Street pollution due to horse urination and droppings was a major health issue in the early 1900s. In New York, for instance, horses daily produced 2.5 million pounds of manure and 60,000 gallons of urine. This accounted for 2/3 of all street filth. Roads were frequently clogged by dead horse carcasses - some 15,000 dead animals being removed from the streets each year. (Flink 1988). Infectious diseases such as typhoid, tetanus and tuberculosis were known to be harboured and carried via dried excreta. Taking the form of airborne dust, it passed through nasal passages to infect the lungs (Flink 1988; McShane 1994). At that time people could neither know nor guess at the health problems associated with mass car use. Hence, public opinion viewed horses negatively and the car positively.
Along with the car, a major source of greenhouse emissions is refrigeration. The physics of mechanical refrigeration are simple. A liquid refrigerant evaporates as it moves through pipes, sucking heat from an inner compartment and dissipating it through external coils. An electrically powered compressor then turns the gas into a liquid, and the cycle begins anew. The first refrigerants were sulphur dioxide and ammonia. These were known toxic agents. When introduced in the 1930s, chlorofluorocarbons (CFCs) were hailed as a new, safe alternative. In 1973 it was first realised that CFCs could reach the upper layers of the atmosphere and destroy ozone, and it was not until the 1980s that a sufficient body of empirical evidence was collected to indicate that this was actually happening in practice (Glynn, 2002).

The existence of pollution thresholds provides a key dynamic for policy change. At some point the negative externalities (in the form of pollution) of adoption become noticeable and continue to increase as the technology \( j \) continues to diffuse,

\[
p_j = \max\{0, p_j - p_j \min\} \quad (4)
\]

where:
- \( \hat{p}_j \) is the observed level of pollution that is generated by \( n \) users of technology \( j \)
- \( p_j \) is the real level of pollution generated by \( n \) users of technology \( j \)
- \( p_j \min \) is the threshold

As agents learn about and better understand the causes of the pollution, so opinion about the technology changes. Environmental opinion takes into account the observed pollution associated with different sets of technology products. Where there is a discrete choice between an old technology (\( \hat{p}_o \)) and a new technology (\( \hat{p}_i \)), environmental opinion is

\[
\text{environmental opinion} = \hat{p}_o - \hat{p}_i \quad (5)
\]

Substituting into (3) we derive

\[
pol_t = f(pol_{t-1}, \hat{p}_o - \hat{p}_i) \quad (6)
\]

Changes in public opinion are important because they affect the probability of future election. This puts pressure on policy makers to revise policy, possibly even leading to new world views that champion the emergence of new alternatives that are more environmentally benign. In this event, there is a major break with past policy. Of course, the alternatives that emerge may themselves have negative environmental impacts, which can only be identified as they diffuse. This can in turn lead to another revision of mental models and policies in the future.
Placing this discussion within the co-evolutionary framework, the changing views of policy makers are linked to, and interact with, the changing views of consumers and entrepreneurs. Consumers and entrepreneurs are, after all, the majority of voters and like policy makers they are influenced by the activities of environmental lobby groups, the media and others who to a large extent shape public opinion. This has important consequences for the frequency and timing of successions. A new technology will quickly displace an established technology if policy makers, consumers and existing producers develop a new set of mental models around a new technology.

Whether or not a shift in policy actually occurs depends on how the forces for change play out against the countervailing and forces for path dependency. These are captured in equation 3 where, on the one hand, a change in opinion is a force for radical change while, on the other, past policy decisions and election voting are forces for continuing path dependency along the old technology trajectory. Empirically, we observe that radical upheavals are not the usual case and, as already stated, there are good reasons why humans do not engage in constant social upheavals. Rather than jettisoning an established technology in favour of a new alternative, a common initial response is to try to find technology fixes for the worst aspects of the established technology.

Let us next consider the drivers of consumer and firm behaviour and action within the co-evolutionary policy framework.

### 5.1.2 Consumers

There is a population of individual consumers. This is assumed to be fixed in size. Each individual consumer evaluates, and chooses between, a set of alternative consumption possibilities in each time period. These distinct consumption possibilities are associated with different group lifestyles or consumer types (as we shall call them). A consumer type is tied to the use of a particular technology. The introduction of a new technology facilitates the development of a new consumer type. A new consumer type will grow if it is supplied by firms with good quality technology products at affordable prices, and there is a supportive legislative policy (or, at least there is not a discriminatory policy). If a new consumer type continues to attract individual consumers, it will grow and eventually displace the old, established consumer types (a related approach has been developed by Aversi et al. 1999).

Note how this approach differs to the Arthur model (equation 1). Here individual tastes and preferences are not assumed to be innate and fixed from the outset. Tastes and preferences evolve over time as individuals have new experiences with radically new technology products that they come into contact with. This is done through individuals joining and leaving consumer types to which other individual consumers belong. These other consumers will also be learning about new preferences over time. This approach is very much within the spirit of Becker and his work on social economics (see, Becker 1996).
In each period, an individual consumer $i$ evaluates a set of existing consumer types ($T_1, T_2, \ldots T_t$). The payoff $\Pi_j$ associated with a consumer type using technology $j$ at time $t$ is

$$\Pi_{jt} = c_j + r_{jt} - p_{jt}$$  

(7)

where 

$$c_j = \frac{c_j^*}{p_j} - \frac{c_j}{p_j}$$

$$r_{jt} = an(b - n)$$

$c_j^*$ is the optimum quality/price combination for consumer type $j$

$c_j$ is the current quality/price combination currently offered by firms to consumer type $j$ in period $t$

$r_{jt}$ is the returns to adoption associated with consumer type $j$ in period $t$.

$p_j$ is the observed level of pollution that is generated by $n$ users of technology $j$

The first term ($c_j$) on the right hand side of (7) captures the private good aspect of consumption while the second and third terms ($r_{jt}$ and $p_j$) capture the public good aspect of consumption.

$r_{jt}$ is a quadratic function of the number of consumers that have previously joined this consumer type. This captures both the positive and negative externalities discussed in section 2. Initially, the positive network utility discussed by Arthur dominates. However, as increasing numbers of individual consumers join type $j$ so the negative externality starts to dominate. In terms of the car, the most obvious negative externality effect is traffic congestion caused by other car users simultaneously commuting to and from work, and to and from holiday destinations. There may also be a snob effect of the type discussed by Liebenstein. In the presence of negative externalities, there is an upper limit on $r$. What is more, there may eventually be a decline in the value of $r$ as increasing numbers of users continue to join this type. If this is the case, then there is a direct incentive for individual consumers to search for alternative consumer types. Here lies the potential for a group of consumers being willing to experiment with, and adopt, a new technological alternative. Ironically, through its very success, an old technology regime lays the seeds of its own destruction.

An individual consumer will decide to join a new technology consumer type $T_1$ or an old technology consumer type $T_0$. 

30
Alternative service characteristics and new consumer types

We need to be more precise about the meaning of the term ‘quality’. Saviotti-Pyka (2004) and Windrum-Birchenhall (2005) use Lancaster’s characteristics approach (1971). Lancaster observed that a product is not demanded for itself but because of the stream of services that it provides the users over its lifetime. This gives us a precise meaning of $C_j$. Windrum (1999) and Windrum-Birchenhall (2005) suggest that what distinguishes alternative technologies is the distinct sets of service characteristics they offer, i.e. each technology offers something that the other technology cannot. Thus, when comparing old and new technology products, users are comparing the different sets of service characteristics offered by each. Tying this observation to the earlier discussion of consumption possibilities, I suggest there is a relationship between the service characteristics of technology $C_j$ and the consumer type $T_j$ it facilitates.

$$C_j \iff T_j$$

The double arrow indicates that they are not independent and that there is a correspondence between the two sets. Here lies the significance of new technologies: they open up new consumption possibilities. When there are different competing technologies, individual consumers are able to choose between different consumption possibilities (lifestyles) associated with alternative consumer types.

The discussion of the car provided a clear example of this. There are a number of service characteristics that distinguish the car from other (public) modes of urban transport. First, it offers the user a flexible, single source method of travelling between any two points. Second, it is an explicitly individual, rather than collective, form of mobility. These service characteristics facilitated the development of suburban living, turning what had hitherto been little more than been an unfulfilled aspiration into a reality. This new consumer type – the suburbanite - was adopted by the aspiring middle classes. They wished to imitate the upper social groups and move away from the inner cities (which were now left to the working classes). Here social differentiation combined powerful with a snob effect. The middle classes were abandoning one consumption type for another: urban living for suburban living. The adoption of this new consumption type promised a move away from ‘city pollution’ to ‘healthy suburbs’, and the middle classes were actively supported in their ambitions by political elites and the media. As highlighted, a technological succession is associated with the emergence of new consumer classes with new preference sets. This contrasts sharply with technological substitutions, where users adopt a new technology because it better fulfils the same role, increasing consumer utility over an unchanging set of preferences.

Let us consider the distinction made between the private and public consumption components of (7). The service characteristics offered to users by an individual design may include its individual pollution performance. For instance, the Prius hybrid
engine car offers consumers a ‘greener’ option. But the aggregate level of car pollution depends on all the different types of car design that comprise the current stock of cars in use, how many trips (and their distance) are made using the current car stock, and how many trips are made using alternative modes of transport. This distinction between individual and collective (aggregate) is the basis of a well-known paradox in environmental economics. Namely, improvement in the pollution performance of an individual product design may actually lead to an increase in environmental pollution if it leads to a significant increase in the use of pollution contributing products. Further, as noted, environmental impact of technology use is often non-linear, captured by the threshold specification of $p_{jt}$.

5.1.3 Firms

Firms are heterogeneous with respect to the set of service characteristics $C$ that make up their product designs, and the consumer type $T$ that they target. Here we shall assume that firms do not switch target consumer types. This is a stylised fact gleaned from the case studies.

In each period, every firm has a current design, a productive capacity (setting an upper limit on output), and a non-negative inventory of stock carried over from the previous period. The price of its design is determined by a fixed mark-up on the unit cost of production (i.e. prices do not adjust to clear the market). This means that coordination of market supply and demand occurs through quantity adjustments. Firms adjust output and capacity in light of past demand.

Firms compete by offering a combination of service characteristics, with a consequent price, they believe will be more attractive than those offered by their rivals. In this way, a firm effectively offers consumers a distinct point in a multi-dimensional service characteristic / price space. Product innovation is the means by which firms search this multi-dimensional space. Unit cost is the sum of an average fixed cost (a common fixed cost $\Phi$ that includes a fixed cost for innovation, divided by the firm’s level of production $y$) and an average variable cost that is a function of the good’s design (the vector of service characteristics offered by the design). Average variable costs of the design are taken to be independent of the level of production. The average total cost $\overline{TC}$ is given by

---

7 Fixed mark-up pricing is a common feature of a number of evolutionary models. Probably the best-known piece of research in this area is Hall and Hitch (1939). Their study of 38 businesses found that the most common pricing procedure was average cost with a ‘normal’ mark-up. The same finding has appeared in more recent studies in the US and UK. More recently, more than half the 72 US firms (with annual revenues of $10+$ million) interviewed by Blinder (1991) reported that cost-based pricing was a moderate or very important factor in explaining price adjustment, while 37% of respondents in the Hall, Walsh, and Yates (1997) study of 654 UK companies use a cost-based pricing rule.

8 In order to simply, this average variable cost function (mapping designs on to unit variable cost) is assumed to be a fixed convex function that is common to all firms. The marginal cost of each service characteristic $k$ is positive and increasing. The partials of the average cost function are positive, and the diagonals of the Hessian are positive.
\[
\overline{TC} = (\Phi(y) + (\Sigma_k \gamma_k c_k(x_k))) \quad (9)
\]

where \(\gamma_k\) are constants and the \(c_k\) are monotonically increasing, convex functions of the \(k\)th service characteristic. Firms set prices according to a simple mark up rule,

\[
p_{jt} = (1+\eta_{jt}) \times \overline{TC}_{jt} \quad (10)
\]

where \(\overline{TC}_{jt}\) is the \(j\)th firm’s average total cost in period \(t\) and \(\eta_{jt}\) is the \(j\)th firm’s mark up in period \(t\). To simplify, let us assume there is a common and constant mark up, so that \(\eta_{jt} = \eta\).

At the beginning of every period, each firm offers a quantity (a stock \(q_{jt}\) plus current production \(y_{jt}\)) of design \(x_{jt}\) at a price \(p_{jt}\) that reflects both the variable cost of producing the current design and an average fixed cost. Given sales \(s_{jt}\) and the level of production \(y_{jt}\) a firm’s net revenue \(\sigma\) is

\[
\sigma_{jt} = p_{jt}s_{jt} - \overline{TC}_{jt} y_{jt} \quad (11)
\]

This profit is added to its monetary wealth \(M_{jt}\), which changes in each period according to \(M_{jt+1} = M_{jt} + \sigma_{jt}\).

Successful firms, with high levels of sales and production, gain a direct advantage from their lower average fixed costs and (in turn) lower prices, making their goods more attractive to consumers. Where the growth of productive capacity is financed from initial wealth or profits, so a firm with relatively high levels of sales, and thus relatively high profits, will be able to finance a higher growth of capacity. Loss making firms, by contrast, will initially use up their monetary wealth and, once exhausted, will finance itself by reducing (i.e. selling) capacity\(^9\). Once capacity is exhausted, the firm is bankrupt and exits the market.

Each firm is randomly assigned a target consumer class. Its design strategy is to maximise the utility function of this target class. As noted, we will assume that firms do not switch between consumer classes. Consequently, success depends on a firm’s ability to innovative. Product innovation involves the creation and evaluation of new designs in each period. New designs are created through a combination of imitation (of the service characteristics of successful rivals) and through the firm’s own R&D activities. These are modelled using a modified genetic algorithm (see Windrum and Birchenhall, 2005). As a consequence of performing R&D, there is a random mutation in one or more service characteristics. In the evaluation process, the firm uses its knowledge of the utility function of its target consumer class to determine whether the proposed design should be put into production or else the existing design should be retained. In other words, a firm will only implement the proposed design if this raises the utility to the target class.

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\(^9\) In the models of Malerba et al. (1999), and Saviotti and Pyka (2004), this process is tempered by venture capitalists and other financiers. These may bankroll a firm for a sufficient time in order for it to identify a more competitive design.
It is worth emphasising, once again, that a ‘design’ is a particular point in the service characteristic space and not a point in an engineer’s technical space. Windrum and Birchenhall (2005) simplify by assuming that each firm knows the utility function of their target consumer classes but does not know how to implement an optimal design. The technical problem facing the firm is the construction of an optimal design that maximises the utility of the target consumer type given a set of production and innovation costs\(^\text{10}\). Since firms can only alter their current designs through innovative search - the filtered process of imitation and mutation - in design space, there is no guarantee they will produce designs with characteristic / price combinations that are optimal for their target consumer type.

### 5.1.4 Key variables

The framework contains a number of key variables that affect the probability of a succession occurring.

On the consumer side, a necessary precondition for a succession is a set individual consumers who are willing to switch away from an existing consumer type and to experiment with a new type. This situation arises when there are negative externalities to belonging to an established consumption type. In the framework there are two types of negative externalities:

(i) negative externalities associated with the number of previous adopters, such as physical congestion and snob effects. These place an upper limit on \(r\) and can even lead to decreasing returns to \(r\).

(ii) pollution \(p\) generated through the use of artefacts.

The timing of a new technology is therefore important. There may be new entrants with new technology designs, and policy making setting a new policy environment, but if individual consumers are not willing to experiment with these new consumption possibilities, then a succession will not occur.

With regards to firms, timing is also important. A set of interested consumers and an appropriate policy environment is of no value without a set of innovative firms that are willing and capable of developing radical new designs. Factors affecting the probability of a succession in our framework are

(iii) the market entry conditions, notably barriers to entry such as high set up costs due to capital intensity of production, i.e. high fixed costs \(\Phi\) (Windrum and Birchenhall 2005). Malerba et al. (1999) and Saviotti and Pyka (2004) highlight the availability of venture capital is a key factor affecting new start ups (though not established firms).

\(^\text{10}\) This assumes that the whole of the service characteristic space is technically feasible, and that this optimal design is the one that maximises the intrinsic utility of the target consumer class. Recall that improving a service characteristic increases direct utility but also increases cost and price, thereby reducing indirect utility. In the model intrinsic utility is a strictly concave function of the design vector and so the optima will be the unique stationary point of this function.
the quality /price of the initial set of designs offered by new technology entrants. Windrum and Birchenhall (2005) found a trade off exists between the direct utility of the characteristics offered by a product and the indirect utility of product price. Consequently, a new technology, offering superior characteristics, will not necessarily displace an old technology if the price differentials are large.

(v) the subsequent R&D performance of old and new technology firms is an essential factor. New entrants stimulates R&D by old technology firms (the sail ship effect). If new firms are more effective innovators then the probability of a succession is high. However, if the old technology firms are more effective innovators, then a lock out is likely to occur (Windrum and Birchenhall 2005).

(vi) time is a key variable. In Windrum and Birchenhall (2005) a succession is more likely to occur (a) the shorter the time old technology firms have (i.e. prior to new technology firms entering the market) to innovate and develop designs that closely match the preferences of their target consumers, and (b) the longer new firms have to innovate and turn their initial set of designs into a set of designs that are optimal for their target consumer type.

Turning to key variables associated with the policy maker, timing is once again important. A policy change that creates a legislative environment which favours a new technology is a fundamental prerequisite for a succession. The framework captures a number of factors that affecting the probability of this occurring. In equation 3 current environment policy depends on previous environment policy decisions (pol\textsubscript{-1}) and current public opinion about key environmental issues (opin\textsubscript{t}). Given this, the probability of a policy change occurring depends on

(vii) the strength of path dependency pol\textsubscript{-1} on current policy

(viii) the extent to which the policy maker is willing to discount path dependency pol\textsubscript{-1} in favour of changes in current opinion opin\textsubscript{t}

(ix) the extent and speed to opin\textsubscript{t} changes as a consequence of observed environmental pollution \( \hat{p} \) generated through technology use

(x) speed of adjustment from a change in policy view to the implementation of the new policy. As we saw in the case studies, this was relatively quick in the case of CFCs but has been extremely slow in the case of the car.

6. Conclusions

Let us conclude drawing together the policy lessons that can be gleansed from this co-evolutionary approach, and discussing the set of policy instruments that are available to policy makers for promoting technology successions.
To start with, alternative technologies compete with a complex selection environment. This environment contains policy makers, firms, consumers and other agents. A policy maker may be a very important agent within this complex selection environment, but (s)he is still only one agent. Technology successions involve the unfolding of a sequence of technologies which alter the space of service characteristics, thereby facilitating a change in consumption possibilities and lifestyles over time. When successions occur there is the displacement of existing consumer preferences by new consumer classes with alternative preference sets, the displacement of established market firms and production structures by new firms with alternative production structures, and displacement of old policy regimes with new policy regimes. It is, in every sense of the word, a gestalt shift - the replacement of one paradigm of mentalities, behaviours and actions with another.

Policy makers who wish to engage in the promotion of technology successions need to understand the dynamics and these processes and must, as a consequence, engage in a different vision of policy. In traditional political science the policy maker is a rational decision maker who knows with certainty all the available options and the payoffs to each option. This is rather like the farmer who understands perfectly the seasons, knows the optimal time to plant and harvest, which crops to sow, how to control for pests and so on. Here, by contrast, we accept that policy maker is not a rational planner with perfect information but a boundedly rational agent that operates in a world of Knightian uncertainty. The policy maker is an agent engaged in the search for new possibilities – hopefully ones that are more environmentally friendly that the current options, although this can never be truly known ex ante. The more appropriate image for this policy maker is the explorative hunter of the unknown. It is a process of continual, ongoing search in an environment that is dynamically changing over time.

Within this conceptual framework, what are limitations and opportunities of policy? The case studies on refrigerants and the car provide a number of policy insights.

- There is a web of interrelated political, commercial and social interests that co-evolve around an established technology. These generate the path dependencies that support an existing technological trajectory.
- Support for a technology fix is invariably the first reaction of policy makers to the pollution generated by an established technology. If a technology fix cannot be found the legislators will consider more radical solutions.
- Firms do not see the wider picture. Indeed, one should not expect them to see the wider picture. In the case of CFC legislation, for instance, better understanding of the consequences of refrigerants on the ozone layer has been driven by scientific discoveries, by environmental pressure groups, and by policy makers.
- The focus of firms is narrow because R&D and industry position are highly path dependent. As we see for both car and chemical companies, their success has been built on a particular set of knowledge and skills. Further, their industry position rests upon a set of established relationships with consumers, policy makers and other firms along the supply chain. R&D and industry position are invariably
threatened by new, alternative technologies and the entry of new firms. This is why chemical manufacturers continue to champion fluorocarbons and oppose hydrocarbons, and why car manufacturers champion hybrid engines.

- Policy makers try to shape public opinion, but they are also highly sensitive to changes in opinion. In environmental policy, changes in opinion have had a significant impact on policy. Here changes are strongly influenced by scientific discoveries, by interest groups and the media as well as by firms and consumer groups.

- Having said this, the case studies also indicate that the speed of policy changes will be affected by a number of factors. First, there is the time horizon. Changes need to have a fairly immediate impact, or at least be seen to be having an impact. This is the case in the case of setting phase outs for refrigerants (CFCs then HCFs and now HCFCs). This short-termism is driven by the electoral cycle. Since policy makers are looking for re-selection at the next election, policy changes made today must having an impact on the electorate before the next election takes place. Second, the scope of policy change is limited by the availability of alternative technologies. This involves factors beyond the policy maker’s control. Not only must more environmentally benign alternatives be available, but they must be actively championed by (new) firms and consumers if they are to replace existing technologies. Hence, policy makers could legislate for the phasing out of CFCs but were not in a position to positively legislate for an alternative. They are unable to legislate against mass car transport until an alternative is in place and being championed by a key set of firms and consumer types.

- Policy makers support new alternatives on the basis that they ‘appear’ to be more environmentally benign. The actual long-term environmental impact of a new alternative cannot be known ex ante. The pollution impact may not necessarily have been evident in the invention or innovation stages, but becomes apparent in the diffusion stage as producers and consumers continue to experiment with the new technology, possibly combining it in novel ways with other technologies that appear in the diffusion phase. It is ironic that the public health movement, which began in the late 19th century as a reaction to the pollution and disease of overcrowded cities, gave rise to the concept of suburban living which in turn helped to promote the car and the pollution impact that it has had. There is an important policy message here. Shifts in policy, driven by shifts in opinion, may not always turn out to be ideal. Clearly, it would have been easier if one could have known the downsides of mass car transport ex ante but, as stated, they operate in conditions of Knightian uncertainty and so this is simply not possible.

Building on past research, the paper has identified a set of necessary conditions for a succession. Pulling these together,

1. There must be a functional equivalence between the new and the old technology products, e.g. alternative modes of transport and alternative means of refrigerating perishable food.
2. Novelty. The new technology products must offer users new consumption possibilities, based on service characteristics that were not available in the old technology products.

3. The emergence of new consumer types, with individual consumers willing to trade-off the novel consumption possibilities of the new technology against the benefits of an established technology.

4. Windows of opportunity. The probability of a succession occurring varies at different moments in time. These can be related to economic and investment cycles, and to different stages of the life cycle.

5. Consumer dissatisfaction with an established technology will arise if there are negative network externalities, or an upper limit to network externalities has been reached.

6. The pollution generated by an existing set of technology goods is a further factor that can cause consumers to consider a new alternative.

7. New technology firms that enter the market develop new technical competences and new conceptualisations of what the market is, and what it can become.

8. The availability of start-up capital is essential for new firms.

9. Market entry is easier when there are low initial set-up costs (e.g. due to low capital intensity).

10. The quality /price of the initial set of designs offered by new technology entrants must be sufficiently competitive to immediately attract consumers.

11. The relative R&D performance of old and new technology firms. New technology firms must be more successful innovators than old firms. If this is not the case, then improvements in quality/price performance of old technology products will lock out the new technology. This means that new firms must more successfully engage in both product and process innovation.

12. New entrants may enjoy better access to key local/national resources, i.e. wages and other input cost advantages.

13. New entrants may have superior organisational structures that more effectively manage internal and external resources.

14. Superior distribution channels are another key source of competitive advantage.

15. Late market entrants can gain advantages through the formation of strategic alliances. Producers of the same product group can use open licence agreements, while producers of complementary goods can establish interoperability between their designs.
16. Time itself is a key variable. A succession is more likely to occur the shorter is the time old technology firms have to develop an effective set of product designs prior to new technology entry, and the longer new technology firms have to develop a set of designs that are optimal for their target consumer type.

17. New policy models. The development of a new technology paradigm requires the development of a new policy model leading to a shift in policy.

18. The probability of a policy shift depends on the strength of policy path dependency on current policy and the extent to which the policy maker is willing to discount path dependency in favour of changes in environmental opinion (based on new scientific understanding, the actions of interest groups, and the media).

19. There are factors that affect the speed with which changes in environmental opinion translate into policy change.

20. Finally, there are factors affecting the speed of adjustment from a change in policy view to the actual implementation of a new policy view.

Finally, let us consider the set of policies and policy instruments that support technology successions within our co-evolutionary framework. We have discussed the sources of path dependencies and webs of supporting interests for an old technology which, once in place and having stabilised over long periods of time, are exceedingly difficult to break. Policy needs to identify and act on these path dependencies. At the same time, policy needs to promote the emergence of new consumer types and new technology firms.

The starting point is policy itself. Promoting new conceptual understandings amongst other agents requires policy makers engage in prior conceptual innovation, in policy and an assessment of policy on firms and consumers. This is an ongoing process of learning. Policy makers cannot know the final outcomes of technology successions ex ante but learn, through interactions with other agents, about their benefits and costs as new technological trajectories unfold. The co-evolutionary learning means policy makers must expect disappointment with regards to initial expectations about a new technology’s environmental impact. These can only be truly identified when technologies actually diffuse (and even then, usually with a time lag). It is important that policy makers adopt a long term view in the formulation of environmental policy. Successions involve unfolding sequences of technological displacements. It is therefore important to evaluate ‘intermediate technologies’. These technologies may not ultimately deliver on their initial environmental promise. However, they may play an important role as a stepping stone to a subsequent technology that is more environmentally benign.

Policy makers need to consider the timing of policy changes. If distinct windows of opportunity exist then there will be an optimal timing and frequency of new technology adoptions. To do this, policy makers must take into account data on successions. This requires the development of new policy indicators, such as the
network externalities of consumers using established and new technologies, and rates of entry and exit amongst old and new technology firms.

Given that government institutions are themselves invariably enmeshed in supporting an established technology, policy change needs to identify and address areas in which government institutions provide complementary goods, or where legislation supports the established technology and locks out alternatives. In the example of the car, we observed that governments are deeply embedded in the provision of both complementary public goods and legislation that maintain car based transport systems. Of course, in advocating change, policy makers must have a viable alternative to champion. Where strong action has been taken successfully, such as road charging in London (the ‘congestion charge’), a viable and readily available alternative was in place. Where this was not the case, such as in the Netherlands, the policy was highly unpopular and failed.

Demand side policies should encourage the development of new consumer types and discourage continuing adherence to old consumer types. The government can lead by example and be purchase of new technologies (Freeman et al. 1982). In some cases, the government may itself be a major customer for an industry. In others it may be an influential purchaser, even if it is not a major customer, and so can give a lead. This was case for the UK Department of Environment when it purchased a number of greenfreeze refrigerators for research purposes in 1993.

More traditional policy instruments are taxes and legislation. By raising taxes on established technologies and subsidising new technologies, policy makers can change the relative prices of old and new technology products and thereby alter their relative quality/price performance. Through environmental legislation, policy makers can ban an established technology outright (as in CFCs) or else specifically target one or more features of the old technology that give rise to pollution. If these taxation and legislation changes are persistent and strong enough, then the policy can lead to a switch in the consumer population away from an old consumer type to a new consumer type.

Government policy may seek to assist the demand side strategies used by new entrants to overcome the network externalities enjoyed by old technology firms. For instance, changes may be made to competition law. The introductory price offer or ‘give away’ (e.g. two for the price of one) is a well-established marketing strategy, used by UK and the US firms, to encourage consumers to try out a new product. This is practice is currently illegal in Germany. Major changes would need to be made to German competition law if its national government were to support the use of this late entrant strategy. Competition law would also need to be changed in order to facilitate the cross-leveraging installed user bases. This was one of the contentious issues in the US Department of Justice and EU cases against Microsoft.

Government policy may seek to alter the length of the investment cycle by legally specifying the maximum period in which consumers to repurchase a particular technology product. This has been used by the Japanese government to speed up the reinvestment cycle for cars. If older vintages are more polluting than newer vintages, changing the scrapping rate will have a significant impact on total pollution. Suppose this policy were applied to an established technology but not to the new technology. It
would change the investment horizon, and hence the net present value of services, in favour of the new technology and against the old technology.

Turning to the supply side, policy should encourage new technology producers and discourage old technology producers. There are various policy instruments available. Some are quite traditional. For instance, taxes and subsides on final goods have already been discussed. Another traditional policy instrument is preferential subsidies to R&D performed by new technology firms.

Less traditional are instruments that are designed to encourage new firm entry. Venture capital is important for new start up firms, though not for existing firms that move into anew market. If there is a shortage of private sector venture capital then government may set up its own venture capital funding. Government may also need to pull out of the public provision of complementary infrastructure and services to the old technology and start developing infrastructure and services that are complementary to the new technology. This may approve highly contentious. For example, each time national governments slow down road building programmes or seek savings in traffic policing, there are outbursts in the media and strong pressure is applied by lobby groups.

To summarise, effective policy-making requires more that a set of strategy recipes. It requires a policy framework in which one can identify the optimal timing and likely impacts of alternative policy strategies. To this end, the paper began the process of outlining such a framework. It is a framework that captures the co-evolutionary learning of interacting agents – policy makers, consumers and firms – as they explore successive sequences of new technologies over time.

The framework captures the twin forces of path dependency and change that characterise technology successions. Understanding these twin forces is central to successful policy formulation. This entails as appreciation of the role policy itself plays in maintaining path dependency to an established technology or in promoting change to a new alternative. Herein lies a fundamental shift in perspective. One must break away from the traditional view of a policy-maker as an independent rational planner. First, the policy maker is not independent but is one agent, amongst a number of interconnected agents, that makes up a complex selection environment. Second, the policy maker does not have perfect information, does not know all of the different options that may become available and does not know the final payoffs associated with different policy choices. Instead, the policy maker is a boundedly rational agent who operates in a world of Knightian uncertainty. Policy makers, like other agents, learn by engaging in the search for new possibilities. Hopefully, these are more environmentally friendly that the current options. Policies promote technologies which appear to be more environmentally friendly ex ante, but this can never be truly known until they have diffused ex post. An analogy was drawn between this type of policy maker and the hunter who explores the unknown. The hunter policy maker in

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11 In practice, it is more efficient to collect taxes and pay subsidies to firms rather than consumers.
engaged in an ongoing search of an ever changing environment – change that is due to the emergence of new technological trajectories.

Understanding the dynamics of technology successions is, of course, essential for policy. In addition, effective policy making requires the identification of windows of opportunity, and the exploitation of deep (trans-trajectory) path dependencies in order to change the behaviour, actions and beliefs of firms, consumers, and government institutions. These have been discussed in the paper, as has the development of new policy indicators. The optimal timing and design of policy requires novel policy indicators, such increasing and decreasing network returns and firm entry/exit, together with insight into that factors that affect these variables. Finally, the paper has identified a set of policy instruments that can be used by policy makers to promote successions to new, more environmentally friendly technologies.
Bibliography


