Waves in Consumption with Interdependence among Consumers*

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Abstract

This paper models the development of consumption when there are interactions among consumers. The consumer recognizes three reference groups: a peer group of similar consumers; a distinction group; and an aspiration group. The interplay of aspiration and distinction can lead to 'waves' in consumption, when, for example, the avant-garde consumption of up-market pioneers is copied by other types of consumer: as the latter aspire to emulate the former, the former in turn seek to distinguish themselves by varying their consumption. A consumption activity may start up-market, and then gradually proceed down the social spectrum. More complex patterns with continuing cycles in consumption can also be found. This model is not only applicable to the consumption behaviour of an elite (or would-be elite) but is relevant in a wide range of consumption settings.

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1 Introduction

The consumer of mainstream economic analysis is generally assumed to have fixed tastes, and to enjoy his or her consumption essentially in private. A wide body of literature has recognized, however, that consumer behaviour evolves over time, and that consumption is an inherently social activity. Indeed, many writers analyze these two phenomena together, because they believe that social interdependencies in consumption are one of the main agents for change in consumer behaviour. An individual's utility from consumption of certain goods is affected by the behaviour of other groups of consumers, and there are several aspects to this interdependence. Some activities become more desirable when they can be shared with a group of peers, and this associative motive plays an important role in the analysis of bandwagon behaviour (Liebenstein, 1950). Again, some activities become more desirable if they allow the consumer to emulate the consumption of an elite that he or she aspires to join. By contrast, some activities become more desirable when the individual can, through wealth or personal endowments, out-shine his peers: Smith (1776) remarks that, "the chief enjoyment of riches consists in the parade of riches", and this phenomenon was studied by Veblen (1899). Or equally, some distinctive activities are desirable because even if they do not cause the consumer to out-shine any peers, they sustain a desire for distinction which Marshall (1920) and Senior (1863) described as, "a feeling which ... may be pronounced to be the most powerful of human passions." The key to understanding these different effects is to recognize that the individual's consumption decisions can depend on the behaviour of specific groups, rather than on other consumers as a mass. In a general way, we can characterize these influences as arising from three specific groups: a peer group of similar consumers with whom the consumer wishes to share consumption activities; a distinction group from which the consumer wishes to distinguish himself/herself; and an aspiration group, to which the consumer does not belong but wishes that he/she did, and with whom the consumer would like to share consumption activities.

In this paper we make the convenient simplifying assumption that consumers are arrayed along a scalar spectrum of 'social status', and the individual's concern with the consumption behaviour of other consumers depends on where he and they are located on this spectrum. We are not here referring to traditional class concepts of classical economics: rather, this is a convenient way to work with the association, distinction and aspiration groups referred to above. In a common case the consumer seeks to associate with those who are close in the 'status' spectrum, to distinguish himself/herself from those who are below, and to emulate the consumption behaviour of those above. In general, it may be more appropriate to envisage consumers arrayed over a multi-dimensional 'social status' space, but for analytical simplicity a scalar representation is used here. This paper develops a dynamic discrete choice model of consumption in which peer, distinction and aspiration effects are central in determining individual consumer behaviour. From a model of individual decision-making we generate static and dynamic results on the distribution of the consumption of a good within a population of consumers. The paper is organized as follows. Section 2 surveys some of the literature that describes and analyzes interdependencies in consumption. To motivate the model that follows, Section 3 then gives an example from the history of the prestige car market, where such interdependencies in consumption have important effects on demand. Section 4 then describes the model of consumption in detail. Section 5 presents some results concerning the steady state properties of the model, while Section 6 illustrates some of the dynamic patterns of consumption that the model can generate. Section 7 concludes.

2 Literature on Inter-dependencies in Consumption

While the paradigmatic consumer of modern theory consumes essentially in private, with a utility function that shows independence of the actions of other consumers, economists have continued to recognize the possibility of interdependencies in consumption; it has a history going back at least to Smith. This work can be split into two parts: one focusing on the effects of a consumer's own consumption history on his/her current consumption; and the other on the effects of the consumption patterns of peers and rivals. This mirrors the distinction made by Becker (1996) between the roles of personal capital and social capital in shaping tastes in consumption.

2.1 The consumer's past consumption history

A consumer's history can create inertia in consumption patterns. Duesenberry (1949) recognized that when incomes fall, families run down savings to maintain the standard of consumption to which they have become accustomed. Brown (1952) modelled habit formation in demand behaviour as a positive autoregressive component in a traditional demand model. Friedman's (1957) concept of permanent income can also be seen in this tradition.[1] By contrast, some areas of economic theory (for example Dasgupta and Stiglitz, 1980), recognize that individual consumers can have a demand for variety. While the origin of the demand for diversity is not developed in detail, it can be interpreted in the current context as a desire on the part of the consumer to differentiate his or her current consumption patterns from those of the past. Most of the literature in this tradition has focused on micro-economic results, with less concern on detailed macro-economic consequences, and especially dynamic consequences,

[1]Other important contributions on the endogeneity of preferences include Becker and Murphy (1988), Dockner and Feichtinger (1993), Feichtinger et al. (1995), Gorman (1967), Gintis (1974), Pollak (1970) and von Weizacker (1971).

that follow from them.

2.2 Consumption patterns of peers and rivals

As noted above, Smith, Senior, Marshall and other classics recognized the consumer's desire to be distinctive. In Veblen's (1899) theory of conspicuous consumption, consumption is an activity undertaken to transmit a signal rather than simply to satisfy needs. Conspicuous consumption requires that individuals indulge in consumption activities recognized by their peers. But it also requires that they distinguish their consumption from that of ordinary people. And indeed, it is not enough that consumption simply imitates that of the peer group: there must be imitation and innovation, so that the individual occupies a distinctive place in the group.[2] One interpretation of the desire for distinction is that consumers interact with each other outside the market, and that these interactions affect utility directly.

There is a now a growing body of literature concerned with direct interactions among agents in the economy. Kirman (1997) and Durlauf (1997) provide recent reviews with different emphases. The work in this literature tends not to be about consumption as such, but is related to our concerns in that it addresses the issue that non-market interactions can affect the utilities (or productivities) of agents. This approach has been applied in various contexts: economic growth (Durlauf, 1993); discrete choice problems (Brock and Durlauf, 1995); opinion formation (Kirman, 1993); and technology choice (An and Keifer, 1995). In general, the concern in this work tends to be with equilibrium, and with equilibrium defined in relatively aggregated variables, such as, for example, the proportion of the population using a technology or holding an opinion. In some related regional models there is also a concern with the size of agglomerations (Cowan and Cowan, 1998; David et al., 1998). In general, though, the spaces in these models do not have direction. Externalities are often distance dependent but agents cannot be distinguished in any way other than their distances from each other. To allow for distinction and aspiration effects, though, an agent must be able to distinguish between agents on his 'left' and those on his 'right'. Direction does matter. This paper models this aspect of space, which allows us to have a richer equilibrium concept, and co-relative dynamic concerns, which involve the distribution of consumption over the population of consumers, and in which consumer location is meaningful beyond distance from other consumers. Some recent work on conformity and conventions has revisited the phenomenon of 'fad' behaviour.[3] Granovetter and Soong, (1986) have also examined the evolution of patterns of consumption in a similar way. From a marketing perspective, Miller at al. (1993) make an important

[2] This idea re-appears in the work of Liebenstein (1950), Mason (1981), Earl (1986), Bagwell and Bernheim (1996), and Ireland (1994), amongst others.

[3] See for example, Banerjee (1992), Bernheim (1994), Corneo and Jeanne (1997a, 1997b), Young (1993).

contribution “Towards Formalizing Fashion Theory” and some of the phenomena of aspiration and distinction analyzed in this paper are also examined there.[4]

Much of this work on conformity and convention, while examining peer, and to some extent distinction and aspiration effects, has focused heavily on equilibria and the possibility of multiplicities. There has been significantly less attention paid to dynamics, however, and this is part of the goal of the present paper. It is also the case that much of the literature on fads and conformity relies heavily on information contagion. Fads and imitation take place because private information is considered inadequate for decision-making. Public information, and other agents’ private information is inferred from public behaviour, and this can create bandwagons or surges in activity, as common behaviour is interpreted as behaviour that has high payoff. We model a situation in which surges and waves in behaviour can arise even when all agents have good information about the properties of the good.

The type of interdependence driving consumption behaviour, with which we are concerned in this paper, can also be seen in the literature on de facto standards.[5] The concept of network externalities (Katz and Shapiro, 1985) plays a central role in this literature, and recognizes that individual choices among competing products are dependent on the choices of others. Standards emerge because there are economies of scale in joint use — a point recognized earlier by Gaertner (1974). In the standards literature externalities tend to be very simple, however: they are only positive, and apply equally to all members of the economy. Put another way, there are only (positive) peer effects, and every agent is the peer of every other. Two recent exceptions to this characterization are Cowan and Cowan (1998) and David et al. (1998).

To advance beyond the very strong standardization results of the technology choice literature, it is important to recognize heterogeneity among agents, even if only peer effects are being modelled. Akerlof (1997) details a series of ethnographic studies and interpretations of peer effects (which he refers to as conformity effects) and their place in individual decision-making. He emphasizes the importance of heterogeneity in the population, particularly as regards location in a social space. Relative location has a vital impact on the nature of the externalities of one agent’s behaviour on another. His concern, however, is equilibrium, and the simple models he presents make no attempt at dynamic analysis. They are simply used to illustrate the possible existence of multiple or inefficient equilibria.

The reader should bear in mind that sociologists have made much progress in recognizing the social and interdependent nature of consumption (Douglas, 1975; Granovetter, 1978; Bourdieu, 1984). In Bourdieu’s analysis (1984), taste is driven in part by the desire for distinction

[4]Other contributions to the economic analysis of fashion cycles include Bikhchandani et al. (1992), Coelho and McClure (1993), Cowan et al. (1997) and Pesendorfer (1995).

[5]See for example Arthur, 1989; Cowan, 1991; David, 1985; Farrell and Saloner, 1985.

and peer group reference, and that gives rise to an explicitly evolutionary character of consumption patterns. But this last theory lacks the power of a quantitative modelling framework that an economic theory of consumption can bring.

The present paper, in contrast to most of the work cited above, focuses explicitly on dynamics. We provide analytic results not only on equilibria, but also on the dynamics by which equilibrium is reached. We draw particular attention to 'waves' in consumption, their shape, duration and amplitude, and on the relationship between the form of external effects and the types of waves that occur. In contrast to much of the conformity literature, we generate these results from a model in which information, both about the properties of the good and about what other agents are doing, is good. Further, we add to the small, but growing, group of models with non-anonymous interactions. Pecuniary externalities are anonymous, in the sense that a price change affects all agents equally. Technical externalities are also generally modelled as having that property. In the present model this is not so — the behaviour of an agent affects different agents differentially.

3 A Motivating Example: The Prestige Car

In the model developed in this paper the consumer's choice between different goods is influenced by the pattern of who owns what at present. To motivate the model, we shall briefly discuss an example from the history of the prestige car market. For a sizeable proportion of consumers, the car is a source of prestige. In Europe, the share of the five main 'prestige' segments in total car sales (by volume) rose from 12 percent in 1988 to 15-16 percent in 1997 (EIU, 1994, 1998).[6] Admittedly, consumers are increasingly reluctant to admit having chosen a car for reasons of prestige, but marketers are convinced that prestige remains a powerful motive in the car market (Windecker, 1997). As one example, Rosecky and King (1996) find that for US buyers of European prestige cars, the high prestige of these cars (compared to domestic cars) is an important factor in decision-making.

For most consumers the choice of car is a discrete choice, and it is helpful to break the decision into a sequence of nested stages. First, the consumer decides whether to buy a prestige car or just an ordinary car. Second, if the decision is 'prestige', the next stage is to decide what category of prestige car: executive, luxury, specialist sports, dual-purpose utility/sports, or multi-purpose? Third, conditional on the choice of category, the next stage is to decide which brand and model. The model developed in this paper is most relevant to stage three.

[6] The prestige share by value would of course be higher. Moreover this figure may underestimate the importance of prestige as it doesn't count the 'prestige' models in other segments of the car market. In recent years, Audi and Mercedes-Benz, amongst others, have launched 'prestige' cars in other market segments.

The history of the Rolls Royce and Bentley cars provides an interesting example. Originally the cars were manufactured by separate companies, but in 1931 Bentley became a subsidiary of Rolls Royce. After World War II, the designs of the two brands began to converge, and in 1955, Rolls Royce launched the Rolls Royce Silver Cloud and Bentley S-type. These cars were nearly identical, apart from a few design details. The only two differences that most consumers would be aware of were: (a) the Rolls Royce had an imposing classical radiator grill, while the Bentley had a more subdued and 'understated' design; (b) the Rolls Royce had a 'romantic' mascot, the so-called 'Spirit of Ecstasy' while the Bentley had a more modest and modern symbol (Bennett, 1995, p. 159). Moreover there was no significant difference in price. This policy continued for several generations of cars.[7] In the 1980s some slight differences started to reappear, and in 1991 Rolls Royce introduced the Bentley Continental R, which was described by the company as "the first new style Bentley since 1952" (Bennett, 1995, p. 291). This episode allows us to examine the importance of different models while abstracting from any major differences in car design and pricing. The example comes close to one of the special cases we consider in the model, namely that in which there is no inherent preference for one model over the other — preferences are determined solely by their respective externalities.

Source: Data from SMMT (various years) and authors' calculations based on data in Bennett (1995).

Figure 1: Rolls Royce Share of Total Rolls Royce and Bentley Sales

Figure 1 shows the relative sales of Rolls Royce and Bentley cars (by volume) from 1954 to 1996. For consistency with the model developed below, the vertical axis shows the difference in sales relative to the total sales of both, or in an obvious notation, $(R-B)/(R+B)$. In the early years, the Rolls Royce share was small and Bentley accounted for a greater part of the

[7]Subsequent Silver Clouds and Bentley S-types became even more similar. The same applied to the Rolls Royce Silver Shadow and Bentley T Series, the Rolls Royce Corniche and Bentley Corniche/Continental, and the Rolls Royce Silver Spirit and Bentley Mulsanne range.

total, but by about 1959 the market was split equally between the two. During the 1960s, the Rolls Royce share grew rapidly and indeed in the 1970s and early 1980s almost all sales had the Rolls Royce badge. But in the early 1980s the Bentley share started to recover and before the end of the 1980s the balance was back at 50:50. During the 1990s the Bentley share once more became dominant.

What explains this remarkable 'cycle'? It cannot be accounted for by price or design effects; rather, it is a striking example of the association, distinction, and aspiration effects discussed in this paper. Ownership of a prestige car implies membership of a 'club', and hence an important component of prestige car ownership is the identity of fellow club members. From the start, a core belief of the Rolls Royce company was that Rolls Royce cars are, "the most prestigious in the world" (Bennett, 1995, p. 296) while the Bentley, though very prestigious was not quite the same. Faced with a choice between the almost identical RR Silver Cloud and Bentley S-type, most customers opted for the former, believing that this would place them in the more prestigious club. As a result the relative consumption of Rolls Royce models increases sharply. But in the 1960s and 1970s, and especially with the various generations of the Rolls Royce Silver Shadow, the company may have sold too many Rolls Royces, perhaps to the wrong sorts of people, and this debased the brand. The best selling Rolls Royce of the period (the Silver Shadow I) sold some 16,717 cars, which is a very high number for a model of this sort. Swann (2001a) shows that in markets sustained by a demand for distinction, it is essential to ensure that not too many customers come to own the same model.

Furnham and Lewis (1986) describe how the Rolls-Royce became associated with excessively conspicuous consumption, as rock stars and other nouveau riches began to use the 'Rolls' as a means of displaying their arrival. When club members are too brash and too fond of extravagant conspicuous consumption, then we may observe a trend away from goods associated with conspicuousness. In consequence, the very closely related, but more subdued Bentley brand became a surer mark of distinction.[8] So during the 1980s we see a shift in consumption away from the Rolls Royce and back towards the Bentley

Can any other factors account for this 'cycle'? Only *after* the recovery of Bentley's fortunes do we observe design differences emerge. Thus the timing is wrong to ascribe the cycle to changes in the objective properties of the cars. The early downturn in Bentley's fortunes is partially a result of company policy: Bennett (1995) suggests that the Rolls Royce company did not try very hard to 'sell' the Bentley models during the 1970s.[9] Having said that, this

[8]We can see a similar phenomenon at a more macro level. EIU (1998) argue that part of the reason for the trend away from luxury car sales towards other types of 'prestige' cars is that consumers are wary of what they perceive as a resentment of over-conspicuous consumption.

[9]Bennett (1995, p. 250) quotes the Managing Director of Rolls Royce in the 1970s saying of one model: "if anyone asked us for a Bentley, we would certainly quote him a price". But then the Rolls Royce company had never felt it necessary to adopt an active selling strategy for any of their cars. Their belief was that,

trend was certainly not just driven by the company. Bennett (1995, p. 6) describes how Bentley models were at one time 'converted' by owners so that they would look like the more prestigious Rolls Royce. Moreover, Bennett (1995, p. 249) also describes how the vast majority of customers for the Corniche model actively expressed a preference for the Rolls Royce 'badge'. Thus while there may be other things contributing to the trends we see in the data it seems that the real driving forces have to do with aspiration and distinction effects among car buyers.

This phenomenon is not unique to Rolls Royce. The recent experience of BMW in the UK car market shows how an attractive club runs the risk of losing its distinctiveness. In 1997, BMW announced their plans for a "year of consolidation" in 1998 (Financial Times, 1997). BMW sales in the UK would be pegged at 1997 levels even though the firm could realistically sell twice that number (Independent, 1997). The aim here was clearly to reduce the risk of devaluing the brand. Steadily increasing sales would mean that second hand BMWs (if not new ones) were getting into the 'wrong hands', and hence that BMW ownership was no longer the guaranteed mark of distinction it had been in the past. The same point had been made, a decade earlier, by Bayley (1986) who described how the carefully nurtured image of the BMW owner was being damaged each time an 'undesirable' gets his hands on an old BMW.

4 A Model of Inter-dependencies in Consumption

In this section, we set out the basic elements of our model, and then show how our model of discrete choice can be defined in terms of differential utility. Finally, we derive equations defining the dynamics of consumption.

The model developed below is a dynamic discrete choice model with externalities. At time zero two durables appear, labelled R and B (with obvious reference to the previous section!) They are substitutes and supplied at fixed prices π_R and π_B. Consumers have inelastic unit demand, consuming at all times exactly one unit of either R or B. The expected lifetime of these goods is L, with failure governed by an exponential distribution.[10] Thus the failure rate is $\alpha = 1/L$. Since the population of consumers is large, this means that each period a proportion of consumers α need to decide again whether to consume good R or good B. We shall see that the distribution of consumption evolves over time, as consumers change their behaviour in accordance with the actions of nearby consumers and the realization of a random

"Rolls-Royce do not sell cars — people buy them" (Bennett, 1995, p. 287). It is said that the Ferrari company have a similar strategy. One of the key business principles of Enzo Ferrari, founder of the company, was that he should always make one less car than the market wanted: having estimated that the market for the 50th anniversary Ferrari F50 was 350 cars, the company made 349. See http://www.team.net/www/ktud/ferr.html

[10]Assuming an exponential distribution for failures implicitly assumes time independence. This is not crucial for the results, but greatly simplifies both exposition and development of the model.

variable.

There is a continuum of consumers, distributed over the real line, indexed by s. The scalar s is an incomplete representation of a consumer in that it is insufficient information to predict behaviour, which implies that we can make only probabilistic statements about it. We refer to s as 'social status', and assume that it is unchanging over time.[11]

Because each consumer consumes exactly one unit of one of the two goods, we can, without loss of information, speak of the "dominance of R", that is, the degree to which R is dominant in the market: $p(s,t) = p_R(s,t) - p_B(s,t)$, where $p_R(s,t)$ and $p_B(s,t)$ are the proportions of consumers of type s consuming R and B respectively (this can be thought of as the market shares of the two goods within the market segment defined by consumers of type s). In the consumer choice problem the consumer is concerned only with differential utility, that is, with the utility of R minus the utility of B, and consumes R if the differential utility is positive, B if it is negative.

Differences in utility arise from four sources: whether R is inherently preferred to B; whether R provides higher externality benefits than B; whether R has a lower price than B; and an idiosyncratic component. Assuming that utility is additive in these four components, we can write the differential utility in money metric terms as

$$U(s,t) = g(s) + \phi[s, p(\cdot,t)] - \pi + \epsilon \tag{1}$$

where we use the notation $p(\cdot,t)$ to indicate that $\phi[s, p(\cdot,t)]$ is a functional defined over the entire range of $p(s,t)$.

Addressing each term in turn: for consumers of type s, if the properties of good R suit them better than do the properties of good B, the inherent value of R exceeds that of B and $g(s)$ is positive. Externalities arise through the aspiration and distinction effects discussed above, and if the dominance of R is high among consumers of type $s' > s$ then the aspiration effect will drive $\phi[s,\cdot]$ positive. Similarly if the dominance of R is negative among those consumers, the externality effect, $\phi[s,\cdot]$ will be negative. The distinction effect works in a similar way. (Below we generalize to talk simply of 'externality effects'.) The price term is simply the difference in prices and is self explanatory. Finally, each consumer is subject to idiosyncrasies or 'whims'. That is, even though consumers of type s may have a typical preference for one type of car over another, the degree to which any particular consumer does is idiosyncratic to him, and

[11] We use the term 'social status' as it fits well with the sociological literature on demand determination. This single dimension of heterogeneity could as easily be income, education, or other like variable. That the model uses a scalar to describe agents indicates that they are quite incompletely specified. Agents can be more completely specified by increasing the dimension of s. In principle the analysis is identical, (provided there is always some incompleteness in the specification, as seems likely) but has the cost of considerable notational and analytical inconvenience.

may change in a whimsical fashion from period to period. In the model, ϵ_t is the realization of a random variable representing this whimsical component of utility. We assume that ϵ_t has a continuous, single-peaked, symmetric distribution, a mean of zero, and is independent and identically distributed over time.

At time zero the dominance of R among consumers of type s is given by $p(s,0)$. The genesis of this distribution is unspecified. Over time, this dominance evolves and at time t is defined by $p(s,t)$.

Now consider the consumers who replace their durables between time t and $t+\Delta t$. Define $p^*(s,t)$ as the dominance of R among this sub-population. Consumers choose simultaneously, which means they must make their decisions about the next period on the basis of current knowledge. Following the tradition of evolutionary game theory, we assume that consumers have myopic expectations about $p(\cdot,t)$.[12] These consumers make their utility calculations on the basis that the dominance of R across the social spectrum will remain at $p(\cdot,t)$, but their final decisions are influenced by any whimsical preferences at the moment of purchase $(t+\Delta t)$.

Amongst those who re-choose, the probability of choosing R is given by $\Pr\{\phi[s,p(\cdot,t)]+g(s)-\pi+\epsilon_{t+\Delta t}>0\}$. Since those who re-choose must either select R or B, then $p^*(s,t)=p^*_R(s,t)-p^*_B(s,t)=2p^*_R(s,t)-1$, where $p^*_R(s,t)$ and $p^*_B(s,t)$ are the proportions choosing R and B respectively, amongst those who re-choose at time t.

Hence, the dominance of R among those who re-choose is given by:

$$p^*(s,t+\Delta t)=2\Pr\{\phi[s,p(\cdot,t)]+g(s)-\pi+\epsilon_{t+\Delta t}>0\}-1 \tag{2}$$

Given the assumptions on the density of ϵ, its cumulative distribution will have a standard ogive shape. In order to achieve analytic solutions we use the following linear approximation:

$$\Pr\{\epsilon<x\}=\begin{cases}1 & : \; x\geq 1/(2b)\\ 1/2+bx & : \; 1/(2b)>x>-1/(2b)\\ 0 & : \; -1/(2b)\geq x\end{cases} \tag{3}$$

Hence we can rearrange 2 to obtain:

$$p^*(t)=2\left(\frac{1}{2}+b(\phi(s,p(\cdot,t))+g(s)-\pi)\right)-1=2b(\phi(s,p(\cdot,t))+g(s)-\pi) \tag{4}$$

This has an easy intuitive interpretation. Among those replacing their cars at time $t+\Delta t$, the dominance of R will be higher if: (i) the relative externalities from model R are higher (ϕ); (ii) the relative "quality" of model R is higher (g); and (iii) the relative price of model R is lower(π).

[12] Given that an agent with rational expectations would have to solve simultaneously the problem of every agent, this seems perfectly reasonable, the more so as α gets small.

Now we define the dynamics. Because the durables fail at a rate α, each period a proportion of consumers, $\alpha < 1$, replace their durables, and again need to choose whether to consume R or B. Consider the dominance of R at time t at each status level s: $p(s,t)$. If the economy starts out of equilibrium, the following dynamics will exist:[13]

$$p(s, t + \Delta t) = (1 - \alpha)p(s, t) + \alpha p^*(s, t + \Delta t). \tag{5}$$

The dominance of R is the weighted sum of the dominance among those who do not re-choose, $p(s,t)$ and the dominance among those who do re-choose, $p^*(s, t + \Delta t)$.

Combining equations 4 and 5, and rearranging, we obtain:

$$p(s, t + \Delta t) - p(s, t) = \alpha \left[2b(\phi\left[s, p(\cdot, t)\right] + g(s) - \pi) - p(s, t)\right], \tag{6}$$

This can be simplified by defining $p_n(s) = 2b(g(s) - \pi)$ as the 'natural dominance of R' for consumers of type s. This is the dominance of R that would prevail if there were no externalities. Then, replacing $2\alpha b\phi[s, p(\cdot, t)]$ by $\Phi[s, p(\cdot, t)]$:

$$p(s, t + \Delta t) - p(s, t) = \Phi[s, p(\cdot, t)] + \alpha[p_n(s) - p(s, t)]. \tag{7}$$

This difference equation describes the dynamics of the system. Dividing by Δt to create the Newton quotient, and taking the limit, we can write equation 7 as a differential equation, in which α is the rate at which consumers re-consider their actions:

$$dp(s, t)/dt = \Phi[s, p(\cdot, t)] + \alpha[p_n(s) - p(s, t)], \tag{8}$$

Finally, we make the externality explicit. In what follows we shall assume the following very general form for externalities. A consumer of type s computes the differential externality from owning car R as:

$$\Phi[s, p(\cdot, t)] = \int_{-\infty}^{\infty} f(s' - s)p(s', t)ds' \tag{9}$$

This has an easy intuitive interpretation. The function $f(s' - s)$ describes the value to a consumer of type s to matching the behaviour of a consumer of type s'—the value of belonging to the same club as someone at s'. This value can be positive or negative. If, from the point of view of someone at s, s' represents 'the right crowd' then $f(s' - s)$ will be positive. Someone at s will benefit from doing what the s'-types tend to do. "What the s'-types tend to do" is captured by $p(s', t)$ which measures the dominance of R among consumers of type s'. So in aggregating these externalities for a consumer of type s, we integrate over the whole social

[13] This has a similar structure to the partial adjustment models of investment, first used by Jorgenson and Stephenson (1967).

spectrum ($-\infty < s' < \infty$), and $f(s'-s)$ is weighted by the dominance of R amongst s'-types, to generate the excess value of choosing good R. In equation 9, we are making the assumption that these externality effects are translation independent. That is, the effect of the consumption by s'-types on the utility of s-types depends only on the distance between them, $s'-s$.[14] Hence, combining (8) and (9)

$$dp(s,t)/dt = \int_{-\infty}^{\infty} f(s'-s)p(s',t)ds' - \alpha[p(s,t) - p_n(s)] \tag{10}$$

Equation 10 fully describes the dynamics, and can be solved for the steady state of the system and to describe properties of the path to the steady state. It has an easy intuitive interpretation: the first term captures the changes in the dominance of R attributable to externalities; the second term describes how the actual dominance of R adjusts towards the 'natural dominance'.

5 Propositions about the Steady State

This section gives four useful propositions about the steady state of this model that can be derived from equations 8 and 10. Section 6 will give two additional propositions about the path to the steady state.

Proposition 1: When there are no externalities in consumption, the dominance of R defined over s has an equilibrium density given by $p_n(s)$.

Proof: In equation 8, all inter-consumer interaction is contained in the term $\Phi[s, p(.,t)]$. If that is zero, then equation 8 becomes $dp(s,t)/dt = \alpha\,[p_n(s) - p(s,t)]$, which is a simple partial adjustment equation, converging to $p_n(s)$ since $0 < \alpha < 1$.

The next proposition is obtained from equation 10 by doing a Fourier transform on s and a Laplace transform on t, creating the conjugate variables k and z.

Proposition 2: Externalities between consumers cause the equilibrium dominance of R to deviate from the natural dominance, according to:

[14] The assumption that $f(\cdot)$ depends only on $s'-s$ has implications regarding the extremes of the distribution of agents. Virtually all sources of heterogeneity that might impinge on consumption decisions have finite support. There is a richest person in the world, and his income or wealth is finite. Because the richest person has no one above him, there will be boundary effects that must be taken into account when treating his behaviour. The reaction of the richest person to the fact that he is on a boundary will in general be visible for a certain distance away from the boundary, as his 'altered' behaviour will affect the behaviour of those just beneath him in wealth. (Similarly for the poorest person.) In this paper we will not make any attempt to incorporate this sort of effect, which can in principle be done by adding a function $f_1(s,s')$ which is not translation independent. Doing so raises significant tractability problems. We are thus restricting attention to agents away from the extremes of the support. This can be seen as equivalent to assuming unbounded support.

$$\lim_{t\to\infty} P(k,t) = \frac{\alpha P_n(k)}{\alpha - F(k)} \tag{11}$$

where $F(k)$, $P(k,t)$ and $P_n(k)$ are defined as:

$$F(k) = \int_{-\infty}^{\infty} e^{-iks} f(s) ds, \tag{12}$$

$$P(k,t) = \int_{-\infty}^{\infty} e^{-iks} p(s,t) ds, \tag{13}$$

$$P_n(k) = \int_{-\infty}^{\infty} e^{-iks} p_n(s) ds. \tag{14}$$

The function $F(\cdot)$ is defined in equation 12 above, and k is a conjugate variable defined in the appendix.

Proof: See Appendix [15]

$P(k,t)$ describes how the dominance of R varies with status, but can be hard to interpret because the variable k is not simply related to s. Generally, if there are waves in consumption as represented by $p(s,t)$, the properties of these waves can be seen in $P(k,t)$. Suppose that there are strong aspiration and distinction effects that peak at a distance of s_1 and $-s_1$ respectively—consumers want to be most like those s_1 above them in status, and most unlike those s_1 below them in status. We would expect that to result in a wave of consumption that moves through the population. With this structure, $f(s')$ will have a maximum at $s' = s_1$ and a minimum at $s' = -s_1$. This will translate into $F(k)$ having a peak at $k = \pi/s_1$. Looking at equation 11 this implies that $P(k,t)$ will have a peak at $k = \pi/s_1$. Because all of the transformations involved in deriving these functions are unique, one can work backwards: if $F(k,t)$ has a peak at k_1, then we can infer that the locations of the minimum and maximum of the externality function are roughly $2\pi/k_1$ apart in status (s), and we will observe a wave in consumption having a wavelength $s = 2\pi/k_1$. That is, if at time t, R dominates for consumers of status s_0, it will also dominate for consumers of status $s_0 \pm 2n\pi/k_1$ where n is an integer.

If there are no externalities between consumers, then $f(.) = 0$ and hence $F(k) = 0$. In that case, equation 11 simplifies to $P(k,t) = P_n(k)$. The transformation in footnote 15 is possible and returns $p_n(s)$; the equilibrium dominance of R is equal to the natural dominance, and we recover proposition 1. Alternatively, if $p_n(s) = 0$, then the right hand side of equation 11 is zero. In this case, $P_n(k) = 0$, and the equilibrium dominance of R is zero. However, if there

[15] We can recover $p(s,t)$ with the transformation $p(s,t) = \int_{-\infty}^{\infty} 1/(2\pi) e^{isk} P(k,t) dk$, however it is only possible to do this analytically under specific functional forms. In the absence of specific functional forms it is less easy to interpret that the k-dependent function $P(k,t)$.

are externalities, so that $f(.)$ and $F(k)$ are non-zero, or if the natural dominance of R is not zero, $P_n(k) \neq 0$, then the equilibrium dominance of R will differ from the natural dominance.

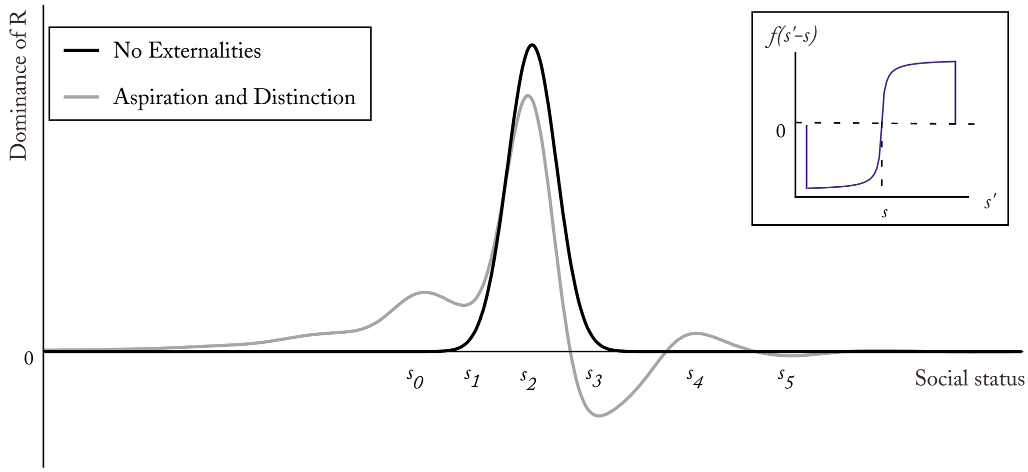

Figure 2: Effects of Externalities in Consumption

Figure 2 shows one example of how the presence of externalities in consumption can 'distort' the steady state (or equilibrium) distribution away from the natural distribution. There are 2 curves in Figure 2. The black curve shows the assumed natural dominance of R. Over most of the social spectrum this is 0 (market shares are equal at 50 %), but consumers between s_1 and s_3 prefer R to B, so R has a positive dominance.

The grey curve shows the steady state (or equilibrium) consumption of R when there are externalities. In this case the externality function is assumed to be:

$$f(s') = \begin{cases} a\left[1 - \frac{1}{s'+1}\right] & : \quad \overline{s} > s' \geq 0 \\ a\left[\frac{1}{1-s'} - 1\right] & : \quad -\overline{s} < s' < 0 \\ 0 & : \quad \text{otherwise} \end{cases}, \tag{15}$$

and is shown in the inset. This is an odd or asymmetric function containing both distinction and aspiration effects. Consumers react adversely to model R when those 'below' them in the social spectrum have a high consumption of R. Equally, consumers react favourably to model R when those 'above' them in the social spectrum have a high consumption of R. At the bottom (or left hand) end of the social spectrum ($s \leq s_1$), the equilibrium consumption of R is above the natural consumption. Consumers in this part of the social spectrum are attracted towards model R because those above them have a relatively high propensity to consume R. Conversely, further up the social spectrum (especially around $s = s_3$), the equilibrium consumption of R is below the natural consumption. Consumers in this part of the spectrum are repelled from R because those below them have a relatively high propensity to consume R. There are some second-order effects too. First, the mode of equilibrium consumption of

R is lower (and slightly to the left of) the mode for the natural consumption. This happens because consumers in this part of the spectrum react against the consumption of model R by those 'below' them (between s_1 and s_2), so that the equilibrium consumption peaks earlier and lower. Second, between s_4 and s_5, the equilibrium consumption of R is slightly above the natural consumption. Here R is attractive due to the under consumption of R (or over consumption of B) by consumers around s_3. There is another aspiration wave left of the mode, as consumers at s_0 emulate those at s_2.

Proposition 3: If $p_n(s) = 0$, then in the steady state, the dominance of R is zero, that is, consumption of R and B are equal for all types of consumer, s.

Proof: This follows directly by substituting $p_n(s) = 0$ into the definition of $P_n(k)$, and doing the transformation described in footnote 15 to $\lim P(k, t)$ in equation 11.

In this case, neither good is inherently preferred, so consumers differentiate between them only on the basis of their respective externalities. One good may enter the market as the more popular, and this popularity may migrate through the population, but will eventually disappear. The Rolls Royce/Bentley episode described in Section 3 fits this quite closely. When the (virtually identical) Rolls Royce Silver Cloud and Bentley S-type were introduced (in 1955), the Rolls Royce became the more prestigious initially, but in due course the balance changed back towards 50:50. The converse to this is that if two goods have different objective properties, or different prices, such that some consumers have an inherent preference of one over the other, then $p_n(s) \neq 0$ for some s, and the 'excess popularity' of the relevant good will survive among some consumers in equilibrium.

Proposition 4: Suppose the difference in inherent utility of the two goods, net of price, is the same for every consumer: $g(s) - \pi = c$. Then the steady state dominance of R is:

$$\lim_{t \to \infty} p(s, t) = \frac{2\alpha bc}{\alpha - \int_{-\infty}^{\infty} f(s) ds} \tag{16}$$

A formal proof can be obtained by substituting $p_n = 2bc$ into the proof of Proposition 2 in the appendix. (Recall that $p_n(s)$ was defined above (just after equation 6) as $2b(g(s) - \pi)$, and hence in this case $p_n = 2bc$.)

Informally, the intuition behind the result can be seen in two steps. The first step is to recognise that if inherent utility is the same for all consumers, then in the steady state the dominance at each status level is the same. Any differences in the level of dominance at different values of s are 'washed away' as the system evolves towards the steady state. To see this, suppose that R is temporarily dominant at a particular social status s_1. As a result of this peak at s_1, there will be a distinction effect at some higher status, $s_2 (> s_1)$ and an aspiration or imitation effect at some lower status, $s_0(< s_1)$. Consider the distinction effect at s_2. This reduces the dominance of R at s_2, but in turn the aspiration of those at s_1 to emulate the consumption of those of higher status means that this reduced dominance at s_2 will also reduce the dominance at s_1. Now consider the aspiration effect at s_0. This increases the dominance of R at s_0, but in turn the desire of those at s_1 to distinguish themselves from those of lower status means that this increased dominance at s_0 will reduce the dominance at s_1. In short, this dynamic is a homogenizing one, and since there is no inherent source of inter-status differences in the dominance of R ($g(s) = c - \pi$ for all s), the equilibrium dominance at each status level is the same.

The second step notes that in the steady state $p(s, t)$ will not change, so we can set $dp(s, t)/dt = 0$ in equation 10 and rearrange to obtain:

$$\alpha[p(s,t) - p_n(s)] = \int_{-\infty}^{\infty} f(s' - s)p(s', t)ds' \tag{17}$$

Now if equilibrium dominance is independent of status, then we can write $\lim p(s, t) = Z$ (independent of s), and hence:

$$\alpha[Z - p_n(s)] = Z \int_{-\infty}^{\infty} f(s' - s)ds' \tag{18}$$

This is easily rearranged to give equation 16.

One obvious implication of Proposition 4 is that the larger is g (the quality premium of R) and the smaller is π (the price premium of R), then the larger is the equilibrium dominance of R. Another more interesting implication of Proposition 4 can be seen by referring back to equation 9. It is clear that the integral $\int f(s)ds$ can be interpreted as the net externality effects that would apply when $p(s, t)$=1; that is, when all consumers consume the same good. If these net effects are positive, and c is positive, then the dominance of R is higher than we would expect in the absence of such externalities. This would be relevant, for example, if R and B are network goods, where consumers benefit from owning the same product as others. Conversely, if the net effects are negative, and c is positive, then the dominance of R is lower than we would expect in the absence of externalities. This would be relevant if distinction effects dominate. Finally, if the net effects are zero, then the integral in equation 16 is zero, and hence the steady state dominance of R depends only on c (quality and price), and not on any externalities.

6 Propositions about Dynamics, with Illustrations

Propositions 1-4 have dealt with the steady state of the system. Propositions 5 and 6 deal with the path to the steady state. The intuition behind these propositions is not immediately obvious, and the easiest way to understand them is to look at some examples of consumption dynamics. Accordingly we shall simply state the propositions here, and then turn to look at some examples of consumption dynamics, which bring out the significance of the propositions.

Proposition 5: Let $f(s'-s)$ be an even function: that is, $f(s'-s) = f(s-s')$. This means that consumers react symmetrically to those above and below them in the status distribution. In this case, the dynamic behaviour of the dominance of R is strictly 'diffusive'. This means that any peaks in consumption in the initial state decay over time, and diffuse a little along the social spectrum, in both directions. Any peaks in the natural rate of consumption grow exponentially over time towards the final (equilibrium) state. But there are no travelling waves.

Proof: See Appendix

Proposition 6: Let $f(s'-s)$ be an odd function: that is, $f(s-s') = -f(s'-s)$, and hence consumers react asymmetrically to those above and those below them in the social spectrum. In this case the dynamic behaviour of the dominance of R exhibits travelling waves. The peaks in the distribution travel steadily across the social spectrum. The speed at which these waves travel depends on α, the rate at which consumers re-evaluate their durable good ownership. The higher is α, the faster the progress of these waves.[16]

Proof: See Appendix

To illustrate Propositions 5 and 6, we show three simulations of the pattern of demand as a function of social status, and how this pattern unfolds over time. In each of these three examples, the assumed initial distribution of consumption for R at time zero is the same. For most types of consumers, neither good dominates, but for a small group at s_2 (toward the right hand end of the social spectrum), the initial propensity to consume R is high so R has a high positive dominance. In each example, moreover, the natural distribution of consumption for R is the same. Over most of the social spectrum, the natural rate of dominance of R is 0, but around s_1 (i.e. to the left of the centre of the spectrum) the natural rate of dominance of R is positive. This pattern is the same as that assumed in Figure 2 above—we assume that consumers of type s_1 value the characteristics of model R more highly than the characteristics of model B, but other consumers see no inherent difference between the two goods. The only

[16] Note that all functions $f(s'-s)$ can be written uniquely as sums of even and odd functions. When $f(s'-s)$ contains both even and odd functions, the solution is the sum of two solutions having the behaviours described in Propositions 5 and 6. The qualitative features of this solution depend on the detailed form and value of the different parts.

difference between these three simulations is in the assumed form of the function $f(\cdot)$, which describes the interactions between different consumers. In Figure 3, $f(\cdot)$ is even, and positive. In this case, as described in Proposition 3, externalities are symmetric: that is, consumers gain positive externalities both from those above and those below them, but the strength of the externality diminishes with distance.[17] This could be considered a powerful peer effect where nearby consumers are thought of as peers, but more distant consumers are not. In Figures 4 and 5, $f(s' - s)$ is odd. As described in Proposition 6, this means that consumers react asymmetrically to those above them and those below them in the social spectrum. In both of these figures, consumers are assumed to receive positive externalities from those above, and negative externalities from those below. There is one important difference between Figures 4 and 5. In Figure 4 these externality effects decrease in strength as social distance increases. In Figure 5, by contrast, these effects increase with distance, but are truncated at a given distance.[18] In each simulation, equation 10 is iterated 350 times, using 401 grades of social status. Figures 3-5, which summarise these simulations, are drawn in the same style as relief maps in a geographical atlas. Darker areas represent high dominance of R; lighter areas low, and possibly negative dominance.[19]

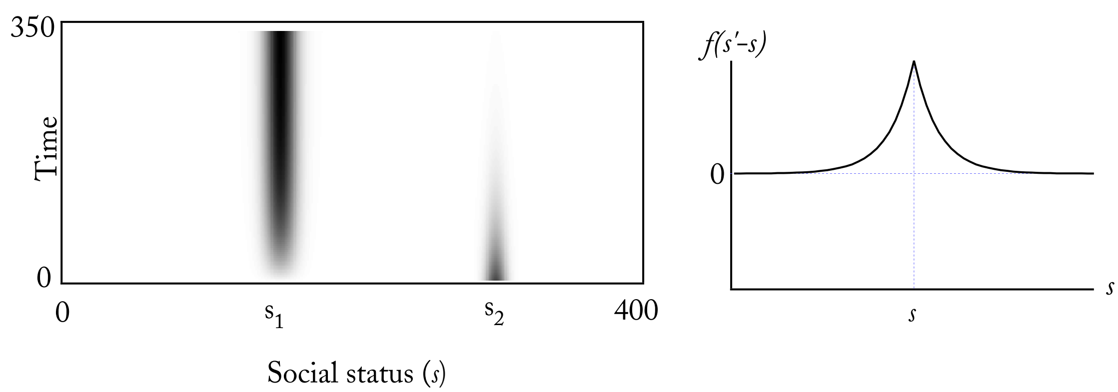

Figure 3: Evolving Dominance of R: Symmetric externalities from nearby consumers

In Figure 3, because the market share of R never falls below 50%, white indicates a dominance of 0 (equal market shares for R and B), whereas black indicates a high dominance of R. In this figure, the initial 'spike' in consumption of R is at s_2, and it spreads a little horizontally, as consumers near to (and on either side of) s_2 also increase their consumption of R. But this increased consumption of R does not spread far from s_2, and then gradually drops

[17]Here $f(s') = a - a/|s'|$ for $-c < s' < c$; $f(0) = a$, and 0 otherwise.

[18]In figure 4 $f(s') = \text{sign}(s')(ae^{-|s'|})$ for $-c < s' < c$; 0 otherwise. In figure 5 $f(s') = \text{sign}(s')(a - a/|s'|)$ for $-c < s' < c$; $f(0) = a$; and 0 otherwise.

[19]Dynamic versions of these graphs can be seen at:
http://www.cgl.uwaterloo.ca/~racowan/ConsumptionWaves.html

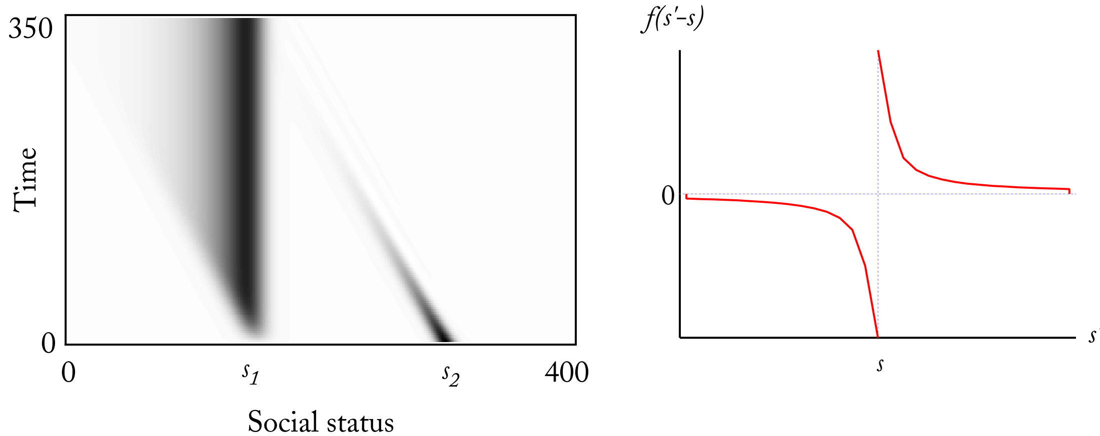

Figure 4: Evolving Dominanance of R: Asymmetric externalities from nearby consumers, $f(\cdot)$ is odd, decreasing in distance

back towards 50 percent. On the other hand, consumption of R around s_1 increases steadily over time, and throughout the simulation, R dominates amongst consumers of type s_1. As indicated above, this is because the inherent properties of R tend to give relatively high utility to those just below the middle of the social spectrum. This example illustrates the point in Proposition 5, that the dynamics are 'diffusive' and that there are no waves in consumption passing steadily down the social spectrum.

In Figure 4, as in the previous figure, the market share of R never falls below 50 percent, so the dominance of R new falls below 0, which is shown in white in the figure. Here, initial dominance of R is 0 except for the 'spike' at s_2, where R dominates. Gradually, those below s_2 start to emulate the behaviour of consumers at s_2. This higher demand for R gradually spreads downmarket in the form of a travelling wave, as new consumers start to emulate the behaviour of those above them on the social spectrum. As this wave progresses downmarket, however, consumers of type s_2 want to distinguish themselves from those below, and accordingly reduce their consumption of R, and consume B instead.[20] As before, and for the same reason, R remains dominant at s_1, though over time the dominance grows slightly and we see the emergence of aspiration effects below s_1.

Note that when, as in Figure 4, the strength of the externality effects in $f(\cdot)$ decreases with distance, the evolution of consumption is smooth in two senses. First, for almost any given status of consumer, demand as a function of time is single peaked: it increases to a maximum and then gradually fades away. These peaks arrive earlier for consumers close to s_2 and later

[20]Of course, if the signs of these externalities are reversed, so that consumers react adversely to the consumption of those 'above' them but react favourably to the consumption of those 'below', then these waves will work their way up market, rather than down.

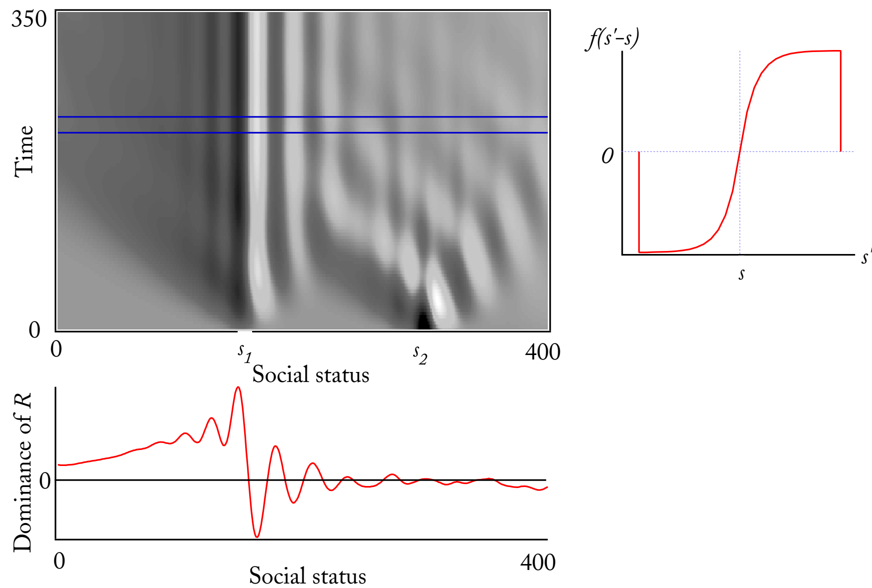

Figure 5: Evolving Dominance of R: Asymmetric externalities from nearby consumers, $f(\cdot)$ is odd, decreasing in distance

for consumers further down market. Second, at any given time demand as a function of social status is also single-peaked over a wide area of the graph above s_1. Early on in the simulations, this peak occurs at a high value of s; later on, it occurs at a lower value of s.

In Figure 5, by contrast, there are times and places where B has the larger market share. The grey scale in the figure thus covers the range -0.004 to $+0.008$ with 0 dominance indicated by a light grey. Once again, initial dominance of R is 0 except for the 'spike' at s_2, where R dominates. Gradually, those below s_2 start to emulate the behaviour of consumers at s_2 and are more likely to consume R, while those above s_2 seek to distinguish themselves from those at s_2 and are more likely to consume B. Here, as before, we observe travelling waves.

In this case (Figure 5), however, when the strength of external effects increase with distance, the evolution of consumption is much less smooth than in Figure 4. Now there are a series of local maxima and minima. Indeed, whether we look at demand as a function of time (for a given social status), or demand as a function of status (at any given time), these functions are rarely if ever single-peaked. On the contrary, there are many 'echo effects' where demand for R grows, declines, and then grows again. The main wave moving from s_2 to s_1 over time is followed by smaller echoes, as people upmarket switch to B as R becomes popular downmarket. Figure 5 holds a second panel which shows the dominance of R over the status axis at one time in the history, indicated by the horizontal lines in the top panel. The single profile shows the importance of the peak in the natural distribution at s_1, the immediate distinction effect to the right of s_1, as well as the echoes of the initial distribution.

The fact that this model can cater for these three very different dynamic patterns is an important property. Empirically speaking, some consumption waves are single-peaked, but others are not. The Rolls Royce and Bentley example discussed in Section 3 (and illustrated in Figure 1) was an example of a single-peaked wave in consumption, first towards greater consumption of the Rolls Royce, and then back again. But looking at the popularity of some veteran cars, on the other hand, we see some of the 'echo effects' illustrated in Figure 5. A car may be popular during its normal lifetime, become passé towards the end its lifetime, but then recover its popularity some years later as a distinctive veteran car, when few are left in circulation.[21]

Even in the case of Figure 5, where the dominance of R does not evolve in a smooth manner, it is possible that the aggregate dominance of R is still smooth. Figure 6 illustrates this by integrating dominance of R (from Figure 5) over the social spectrum, assuming a uniform distribution of consumers along the status axis. As is readily apparent, the aggregate dominance is (essentially) single peaked over time. Good R enjoys a surge in popularity but this peaks early on and then falls slightly as time passes, though in aggregate R remains dominant throughout the simulation.

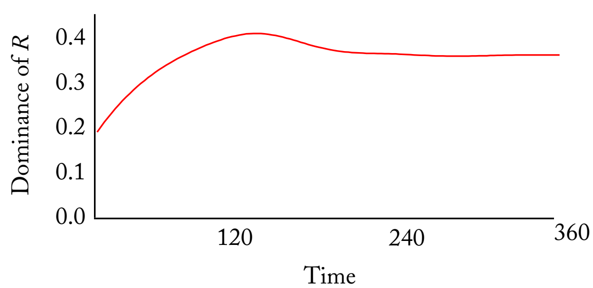

Figure 6: Evolving Aggregate Dominance of R

7 Conclusions

This paper has explored the patterns of demand that emerge when there are social interactions among different consumers. We have concentrated attention on the case where consumer preferences are influenced by the consumption behaviour of three reference groups: a peer

[21]Another interesting example where such 'echo effects' are highly relevant is the market for art. See, as an illustration, the discussion of prices of oil paintings of different artists over time: Cowan (2001) for a theoretical discussion and Swann (2001b) for empirical evidence.

group of similar consumers, with whom the individual shares some consumption activities; a distinction group, from which the individual wishes to distinguish him or herself; and an aspirational group, with whom the individual would like to share consumption activities. The paper has shown how this structure of demand evolves over time and described the nature of the state toward which it tends. The tension between the objective properties of the good and the externalities in consumption determines the final pattern of consumption across the social spectrum. The nature of the externalities determines the properties of the evolution toward that state. The model is relevant to many economic phenomena in which consumer preferences are influenced by at least one of the three reference groups. We have motivated the discussion with reference to the demand for prestige cars, but the model is applicable to many other empirical examples.

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9 Appendix

In this appendix we present proofs of propositions 2, 5 and 6.

Proof of Proposition 2

From equation 10 he change in the dominance of R is given by:

$$\frac{dp(s,t)}{dt} = \int_{-\infty}^{\infty} f(s'-s)p(s',t)ds' - \alpha\left[p(s,t) - p_n(s)\right]. \tag{A1}$$

In order to solve this equation we transform the two variables, s and t. A Fourier transform on s and a Laplace transform on t yield the conjugate variables k and z:

$$P(k,t) = \int_{-\infty}^{\infty} e^{-iks} p(s,t)ds, \tag{A2}$$

and so

$$\mathcal{P}(k,z) = \int_{-\infty}^{\infty} e^{-iks} \int_{0}^{\infty} e^{izt} p(s,t)dtds. \tag{A3}$$

We assume that the imaginary part of z, $Im(z) > 0$ to ensure convergence.

Integrating by parts with respect to t and substituting for $dp(s,t)/dt$ gives:

$$\begin{aligned}
\mathcal{P}(k,z) &= -\frac{1}{iz}\int_{-\infty}^{\infty} e^{-iks}p(s,0)ds - \frac{1}{iz}\int_{-\infty}^{\infty} e^{-iks}\int_{0}^{\infty} e^{izt}\int_{-\infty}^{\infty} f(s-s')p(s',t)dsdtds' \\
&\quad +\frac{1}{iz}\int_{-\infty}^{\infty} e^{-izt}\int_{0}^{\infty} e^{iks}[p(s,t)-p_n(s)]dsdt \\
&= -\frac{1}{iz}P(k,0) - \frac{1}{z^2}P_n(k) + \frac{1}{iz}\mathcal{P}(k,z) - \frac{1}{iz}F(k)\mathcal{P}(k,z) \qquad \text{(A4)}
\end{aligned}$$

where

$$F(k) = \textstyle\int_{-\infty}^{\infty} e^{-iks} f(s)ds \tag{A5}$$

$$P(k,0) = \textstyle\int_{-\infty}^{\infty} e^{-iks} p(s,0)ds \tag{A6}$$

$$P_n(k) = \textstyle\int_{-\infty}^{\infty} e^{-iks} p_n(s)ds \tag{A7}$$

$$. \tag{A8}$$

This can be re-arranged as

$$\mathcal{P}(k,z)(1 - \frac{1}{iz}(\alpha - F(k))) = -\frac{1}{iz}P(k,0) - \frac{\alpha}{z^2}P_n(k). \tag{A9}$$

Thus

$$\mathcal{P}(k,z)[z^2 + iz(\alpha - F(k))] = izP(k,0) - \alpha P_n(k) \tag{A10}$$

or

$$P(k,z) = \frac{izP(k,0) - \alpha P_n(k)}{z^2 + iz(\alpha - F(k))} \tag{A11}$$

To solve this we use the following manipulation: $\frac{Az+B}{z(z+C)} = \frac{X}{Z} + \frac{Y}{Z+C} = \frac{XZ+XC+YZ}{Z(Z+C)}$ where $X + Y = A$; $XC = B$: $X = B/C$; $Y = A - B/C$. In our case, $A = iP_n(k)$; $B = -\alpha P_n(k)$; $C = i(\alpha - F(k))$; $X = i\alpha P_n(k)/(\alpha = F(k))$ and $Y = iP(k,0) - \frac{i\alpha P_n(k)}{\alpha - F(k)}$. Thus we can write

$$\mathcal{P}(k,z) = \frac{i\alpha P_n(k)}{z(\alpha - F(k))} + \frac{i[\alpha - F(k)]P(k,0) - i\alpha P_n(k)}{[z + i(\alpha - F(k))][\alpha - F(k)]}. \tag{A12}$$

Solving as a differential equation, the particular solution for $P(k,t)$ will be a constant. (In the steady state $P(k,t)$ is a constant, since $p(s,t)$ will be a constant.) Thus since $\mathcal{P}(k,z) = \int_0^\infty e^{izt} P(k,t)dt$, we can see that $\mathcal{P}(k,z) = C_1 \int_0^\infty e^{izt}dt$, which gives that $\mathcal{P}(k,z) = C_1(-1/iz)$. From equation A2, this gives that

$$C_1 = \frac{\alpha P_n(k)}{\alpha - F(k)}. \tag{A13}$$

We can write the general solution as $P(k,t) = C_2 e^{-Dt}$. We assume, again to assure convergence, that $Re(D) + Im(z) > 0$. By the same argument,

$$\mathcal{P}(k,z) = C_2 \int_0^\infty e^{-Dt} e^{izt} dt \tag{A14}$$

$$= C_2(-1)/(iz - D). \tag{A15}$$

From equation A2 we can see then that $D = \alpha - F(k)$ and that

$$C_2 = \frac{-\alpha P_n(k) + [\alpha - F(k)]P(k,0)}{\alpha - F(k)} \tag{A16}$$

Thus

$$P(k,t) = \frac{\alpha P_n(k)}{\alpha - F(k)} - \frac{\alpha P_n(k) - [\alpha - F(k)]P(k,0)}{\alpha - F(k)} e^{-(\alpha - F(k))t}. \tag{A17}$$

Then taking the limit as $t \to \infty$, we obtain:

$$\lim_{t\to\infty} P(k,t) = \frac{\alpha P_n(k)}{\alpha - F(k)}, \tag{A18}$$

which is Proposition 2.

Proof of Proposition 5.

This proposition can be seen by examining equation A18 above. It can be re-arranged to give:

$$\begin{aligned} P(k,t) &= \tfrac{\alpha P_n(k)}{\alpha - F(k)} \left[1 - e^{-[\alpha - F(k)]t}\right] + \tfrac{[\alpha - F(k)]P(k,0)}{\alpha - F(k)} e^{-[\alpha - F(k)]t} \\ &= \tfrac{\alpha P_n(k)}{\alpha - F(k)} \left[1 - e^{-[\alpha - F(k)]t}\right] + P(k,0) e^{-[\alpha - F(k)]t} \end{aligned} \tag{A19}$$

The first term shows the growth of the final state (the final state as seen in Proposition 2) and the second term shows the decay of the initial state $p(s, 0)$.

An even valued function $f(\cdot)$ means that the exponent $\alpha - F(k)$ is real valued. Thus any intermediate state can be written as a sum of the decaying initial state and the growing final state. (In general, the initial state changes shape as it decays and the final state changes shape as it grows.) The proposition can be seen from the following argument. Fourier transforms and inverse transforms are unique. That is, for two continuous integrable functions $h1$ and $h2$, if the transform of $h1$ is equal to the transform of $h2$, then $h1 = h2$ (Walker, 1988, Theorem 4.17). Consider the sum of two functions: $u = v + w$ where v and w are respectively exponentially shrinking and growing in time: $v(s,t) = e^{at}v(s, 0)$ and $w(s,t) = (1 - e^{at})w(s, 0)$ with $a < 0$. Transforming u to U, creating the conjugate variable k, we find:

$$U(k,t) = \int_{-\infty}^{\infty} e^{-ik} \left[e^{at}v(s,0) + (1 - e^{at})w(s,0)\right]. \tag{A20}$$

Noting that when $f(\cdot)$ is an even function, $\alpha - F(k)$ is real valued, this is the form of equation (A4), with $v(s, 0)$ being the inverse transform of $P(k, 0)$ — in this case the initial state $p(s, 0)$ — and $w(s, 0)$ being the inverse transform of

$$\alpha P_n(k)/(\alpha - F(k)), \tag{A21}$$

which, by Proposition 2, is the final state.

Proof of Proposition 6

This proposition follows from the following basic property of Fourier transforms. Consider a function $h(s,t)$ that is a simple travelling wave, so that $h(s,t) = h(s + vt, 0)$, where v is a parameter measuring the velocity of the wave. Transforming s in period 0:

$$H(k,0) = \int e^{-iks}h(s,0)ds \tag{A22}$$

In period t:

$$H(k,0) = \int e^{-iks}h(s + vt,0)ds, \tag{A23}$$

which by a change of variables $s' = s + vt$ becomes

$$H(k,0) = \int e^{-ik(s'-vt)} h(s')ds' = e^{ikvt} \int e^{-iks'} h(s')ds' = e^{ikvt} H(k), \tag{A24}$$

which is exactly the form of equation A18 if $f(\cdot)$ is odd, since in that case $F(k)$ is imaginary.