Product Innovation and Macroeconomic Dynamics[‡]

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Abstract

We develop an agent-based macroeconomic model in which product innovation is the fundamental driver of growth and business cycle fluctuations. The model builds on a hedonic approach to the product space and product innovation developed in Georges (2011).

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1. Introduction

Recent evidence points to the importance of product quality and product innovation in explaining firm level dynamics. In this paper we develop an agent-based macroeconomic model in which both growth and business cycle dynamics are grounded in product innovation. We take a hedonic approach to the product space developed in Georges (2011) that is both simple and flexible enough to be suitable for modeling product innovation in the context of a large scale, many agent macroeconomic model.

In the model, product innovation alters the qualities of existing goods and introduces new goods into the product mix. This novelty leads to further adaptation by consumers and firms. In turn, both the innovation and adaptation contribute to complex market dynamics. Quantity adjusted aggregate output exhibits both secular endogenous growth and irregular higher frequency cycles. There is ongoing churning of firms and product market shares, and the emerging distribution of these shares depends on opportunities for niching in the market space.

2. Background

Recent research suggests that product innovation is a pervasive force in modern advanced economies. For example, Hottman et al. (2014) provide evidence that product innovation is a central driver of firm performance. They offer an accounting decomposition that suggests that 50-70% of the variance in firm size at the aggregate level can be attributed to differences in product quality, whereas less than 25% can be attributed to differences in costs of production. Further, in their analysis, individual firm growth is driven predominantly by improvements in product quality. Similarly, Foster etal. (2008) found that firm level demand is a more powerful driver of firm survival than is firm level productivity. Broda and Weinstein (2010) and Bernard, Redding and Schott (2010) further document the substantial pace of churning in product markets with high rates of both product creation and destruction and changes of product scope at the firm level.

We explore the implications of product innovation for growth and business cycle fluctuations in an agent-based macroeconomic model. While there is a literature (e.g., Grossman and Helpman, 1991) that attributes economic growth to growth in product variety, variety is only one expression of product innovation. Both the product turnover and skewed distributions of firm sizes and product market shares that we observe indicate that it is conventional for some products to drive out other products and develop outsized market shares due to superiority in perceived quality. Our agent based approach is well suited to model the types of heterogeneity and churning dynamics that we observe empirically.

Our approach revisits Lancaster (1966a,b). Preferences are defined over a set of product characteristics, and products offer various bundles of these characteristics. As Lancaster notes, the characteristics approach allows for new products to be introduced seamlessly, as new products simply offer new possibilities for the consumption of an unchanging set of characteristics.

Of course there is a large literature on product innovation, and there are a number of existing models that bear some relation to the one developed here. See for example Chen and Chie (2005,2007,2014a,b), Valente (2012), Marengo and Valente (2010), Windrum and Birechenhall (1998), Ciarli, Lorenz, Savona, Valente (2010, 2015), Hidalgo et. al. (2007), Klette and Kortum (2004), Sutton (2007), Akcigit and Kerr (2010), and Acemoglu, Akcigit, Bloom, and Kerr (2013). For comparisons with the current approach, see Georges (2011).

The current paper is in the recent tradition of agent-based macroeconomics. This literature builds macroeconomic models from microfoundations, but in contrast to standard macroeconomic practice, treats the underlying agents as highly heterogeneous, boundedly rational, and adaptive, and does not assume a priori that markets clear. See e.g., Dosi et al. (2005), Delli Gatti et al. (2008), Dawid et al. (2014), and Hommes and Iori (2015).

3. The Macroeconomic Environment

Our goal is to understand the role of product innovation in driving growth and fluctuations in a very simple macroeconomic environment. Here are the fundamental features of the model.

- There are n firms, each of which produces one type of good at any time.
- There are m characteristics of goods that consumers care about. Each good embodies distinct quantities of these characteristics at any given time. Product innovation affects these quantities.
- The probability that a firm experiences a product innovation at any time depends on its recent investments in R&D, which in turn is the outcome of a discrete choice rule.
- Each firm produces with overhead and variable labor. It forecasts the final demand for its product by extrapolating from recent experience, sets its price as a constant mark-up over marginal cost, and plans to produce enough of its good to meet its expected final demand given this price.
- There is a single representative consumer who spends all of her labor income each period on consumption goods and searches for better combinations of products to buy within her budget.
- If a firm becomes insolvent, it exits the market and is replaced by a new entrant.

4. Consumer Preferences

The representative consumer's preferences are defined on the characteristics space. Specifically, the momentary utility from consuming the vector $z \in R_m$ of hedonic characteristics is $u(z)$.[1]

In addition to this utility function, the consumer has a home production function $g(q)$ that maps bundles $q \in R_n$ of products into perceived bundles $z \in R_m$ of the characteristics.[2]

More specifically, we assume that the representative consumer associates with each good i a set of *base characteristic* magnitudes z-base$_i \in R_m$ per unit of the good, as well as a set of *complementarities* with other goods. If the consumer associates good k as as complement to good i, then she associates with the goods pair (i,k) an additional set of characteristic magnitudes z-comp$_{i,k} \in R_m$, per composite unit $q_{i,k} = \theta(q_i, q_k)$ of the two goods (defined below).[3]

Intuitively, a box of spinach may offer a consumer certain quantities of subjectively valued characteristics like nutrition, flavor, and crunchiness. However, the flavor characteristic might also be enhanced by consuming the spinach in combination with a salad dressing, so that the total quantity of flavor achieved by eating these in combination is greater than the sum of the flavor quantities from consuming each separately.

Similarly, in isolation, an Apple iPad may provide a consumer some modest degree of entertainment, but this entertainment value is dramatically enhanced by consuming it along with a personal computer, an internet access subscription, electricity, and so on.

We assume that both base characteristic magnitudes and complementary characteristic magnitudes are additive at the level of the individual good. Thus, for good i and hedonic characteristic j, the consumer perceives

$$z_{i,j} = \text{z-base}_{i,j} \cdot q_i + \sum_k \text{z-comp}_{i,j,k} \cdot q_{i,k}. \tag{1}$$

These characteristic magnitudes are then aggregated over products by a CES aggregator:

$$z_j = \left[\sum_{i=1}^{n} z_{i,j}^{\rho_1} \right]^{1/\rho_1} \tag{2}$$

[1] While we are working with a representative consumer in the present paper for convenience, it is a simple step in the agent-based modeling framework to relax that assumption and allow for idiosyncratic variation of consumer preferences.

[2] This is essentially the approach taken by Lancaster, and shares some similarities with others such as Becker (1965) and Strotz (1957). The primary deviation of our approach from that of Lancaster is the construction of our home production function $g(q)$.

[3] This vector is associated with good i, and it is convenient to assume that the complementarities are independent across goods (i.e., that the vectors z-comp$_{i,k}$ and z-comp$_{k,i}$ are independent).

with $\rho_1 < 1$. Equations (1) and (2) define the mapping $g(q)$ introduced above. The CES form of (2) introduces some taste for variety across products. [4]

We assume that the utility function u for the representative consumer over hedonic characteristics is also CES, so that

$$u = \left[\sum_{j=1}^{m} (z_j + \bar{z}_j)^{\rho_2} \right]^{1/\rho_2} \tag{3}$$

where $\bar{z}_j$ is a shifter for characteristic j (see Jackson, 1984), and $\rho_2 < 1$. Thus, utility takes a nested CES form. Consumers value variety in both hedonic characteristics and in products.

Finally, we specify the aggregator for complements $\theta(q_i, q_k)$ as floor(min($q_i \cdot \frac{1}{\lambda}, q_k \cdot \frac{1}{\lambda}$)) $\cdot \lambda$. I.e., complementarities are defined per common (fractional) unit λ consumed.[5]

5. Product Innovation

A product innovation takes the form of the creation of a new or improved product that, from the point of view of the consumer, combines a new set of characteristics, or enhances an existing set of characteristics, when consumed individually or jointly with other products. The new product will be successful if it is perceived as offering utility (in combination with other goods) at lower cost than current alternatives. The product may fail due to high cost, poor search by consumers, or poor timing in terms of the availability or desirability of complimentary goods.

In the present paper, at any time the base and complementary set of hedonic characteristic magnitudes (z-base$_i$ and z-comp$_{i,k}$) associated by the consumer with good i are coded as m dimensional vectors of integers. These characteristics vectors are randomly initialized at the beginning of the simulation.

A product innovation is then a set of random (integer) increments (positive or negative) to one or more elements of z-base$_i$ or z-comp$_{i,k}$. Product innovation for continuing firms is strictly by mutation. Product innovations can be positive or negative. I.e., firms can mistakenly make changes to their products that consumers do not like. However, there is a floor of zero on characteristic values. Further, innovations operate through preferential attachment; for a firm that experiences a

[4] Note that if $\rho_1 = 1$, the number of viable products in the economy would be strongly limited by the number of hedonic elements, as in Lancaster, who employs a linear activity analysis to link goods and characteristics.

[5] Note that this introduces a (fractional) integer constraint on the consumer's optimization and search problem. $\lambda > 0$ but need not be less than one.

product innovation, there is a greater likelihood of mutation of non-zero hedonic elements.[6]

6. R&D

The R&D investment choice is binary – in a given period a firm either does or does not engage in a fixed amount of R&D. If a firm engages in R&D in a given period, it incurs additional overhead labor costs R in that period.

In making its R&D investment decision at any time, the firm compares the recent profit and R&D experiences of other firms and acts according to a discrete choice rule. Specifically, firms observe the average recent profits π_H and π_L of other firms with relatively high and low recent R&D activity. Firms in the lower profit group switch their R&D behavior with a probability related to the profitability differential between the two groups. Specifically, they switch behavior with probability $2\Phi - 1$, where

$$\Phi = \frac{e^{\gamma \pi_1}}{e^{\gamma \pi_1} + e^{\gamma \pi_2}}$$

$\gamma > 0$ measures the intensity of choice and π_1 and π_2 are measures of the average recent profits of the high and low profit R%D groups.[7] There is additionally some random variation in R&D choice.

In turn, the probability that a firm experiences product innovation is increasing in its recent R&D activity.[8]

7. Production

Each firm i produces its good with labor subject to a momentarily fixed labor productivity $A_{i,t}$, and incurs a fixed overhead labor cost H. In this paper, our focus is on product innovation rather than process innovation. Consequently, we suppress process innovation and hold $A_{i,t}$ constant over time. [9]

8. Consumer Search

The consumer spends her entire income each period and selects the shares of her income to spend on each good. Each period, she experiments with random

[6] This weak form of preferential attachment supports specialization in the hedonic quality space.

[7] I.e., if $\pi_H > \pi_L$, then $\pi_1 = \pi_H$ and $\pi_2 = \pi_L$, and firms with relatively low recent R&D activity switch R&D on with a probability that is greater the larger is the difference between π_1 and π_2.

[8] Each firm's recent profits and activity are (respectively) measured as exponentially weighted moving averages of its past profits and activity.

[9] Process innovation that affects $A_{i,t}$ across firms and over time can easily be introduced.

variations on her current set of shares. Specifically, she considers randomly shifting consumption shares between some number of goods, over some number of trials, and selects among those trials the set of shares that yields the highest utility with her current income. While the consumer engages in limited undirected search and is not able to globally maximize utility each period, she can always stick to her current share mix, and so never selects new share mixes that reduce utility below the utility afforded by the current one. I.e., the experimentation is a thought exercise not an act of physical trial and error.

9. Features of the Model

If we eliminate all heterogeneity in the model, there is a steady state equilibrium which is stable under the simple dynamics described above. Aggregate output is a multiple of the overhead labor costs H and R and is independent of product quality. See Appendix I for details. Quality adjusted output and consumer utility, on the other hand, will grow over time in equilibrium as product quality improves.

With firm heterogeneity, the evolution of the hedonic characteristics of firms' products will influence product market shares as well as aggregate activity and living standards.

The stochastic evolution of product quality with zero reflective lower bounds on individual characteristic magnitudes will tend to generate skewness in the distribution of individual product qualities and thus in the distribution of market shares.

Working against the skewness of the distribution of product shares are the variety-loving aspect of consumer preferences and the number of product characteristics and complementarities. The greater the number of characteristics, the greater the opportunities for individual firms to find niches in the characteristics space. A small number of characteristics relative to the number of products creates a "winner take all" environment in which firms compete head to head in a small number of dimensions, whereas a large number of characteristics may create opportunity for the development of a (so called) "long tail" of niche products.[10]

Ultimately, the evolution of firm sizes and product shares will depend on the interaction between the evolution of individual product characteristics, complementarities, and productivity as well as the entry and exit processes.

Turning to aggregate activity, with heterogeneity, there are several channels through which product innovation may be a source of output fluctuations.

First, product innovation produces ongoing changes in the pattern of demand across goods. It takes time for production to adjust to the changing pattern resulting

[10] A recent literature argues that the growth of internet retail has allowed niche products that better suit existing consumer preferences to become profitable, eroding the market shares of more broadly popular "superstar" products (Brynjolfsson, Hu and Smith (2010), Brynjolfsson, Hu, and Simester (2011))

in both direct and indirect effects on output. Further, as demand patterns change, demand may shift between goods with different production technologies.[11]

A second mechanism is that investment has a direct impact on aggregate demand. Since R&D investment decisions are conditioned by social learning, there can be cyclical herding effects in this model.

Third, if network effects are large or product innovation results in highly skewed distributions of firm sizes and product shares, then idiosyncratic firm level fluctuations may not wash out in the aggregate, even as the number of firms and products grows large.[12]

We exclude other sources of business cycle fluctuations and growth from the model to focus on the role of product innovation.

10. Some Simulation Results

Runs from a representative agent baseline version of the model behave as expected. If all firms have the same parameters and the same productivities and hedonic qualities and all engage in R&D, then output converges to the analytical equilibrium discussed in Appendix I.

For the heterogeneous firms model, ongoing endogenous innovation tends to generate stochastic growth in consumer utility and ongoing fluctuations in total output. As the number of firms increases, the output fluctuations become increasingly dominated by variations in R%D investment spending through the herding effect noted above.

Figure 1 is produced from a representative run with 1000 firms. In this case the number of product characteristics is 50, $\rho_1 = \rho_2 = 0.8$, and mutation is multiplicative.[13] There is no variation in labor productivity $A_{i,t}$ over time t or across firms i.

[11] Below, we suppress the latter effect, standardizing productivity across firms in order to focus more directly on product innovation.

[12] Intuitively, if some firms or sectors remain large and/or central to the economy, even under highly disaggregated measurement, then idiosyncratic shocks will have aggregate effects. For formalizations, see for example Gabaix (2011), Carvalho and Gabaix (2010), Delli Gatti et. al. (2008), Acemoglu, Carvalho, Ozdaglar, and Tahbaz-Salehi (2012), Acemolglu, Akcigit, and Kerr (2015), and Horvath (2000).

[13] The number of firm in this simulation is small (1000), but can easily be scaled up to several million. Similarly the number of hedonic characteristics (50) can be increased easily (though in both cases, of course, at some computational cost).

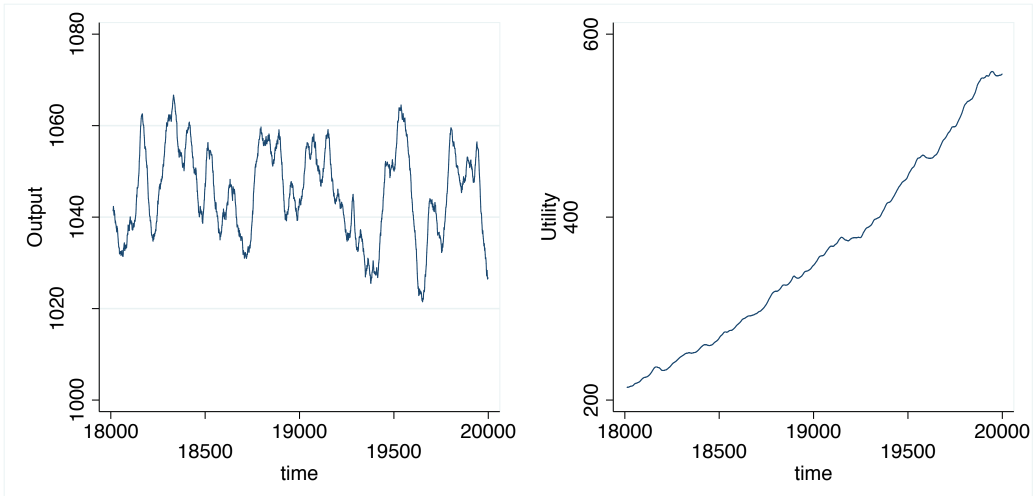

Figure 1: Representative run. Output and utility, for rounds 18,000 – 20,000. Output is measured weekly as average output for the last quarter. The number of hedonic characteristics is $m = 50$ and the intensity of choice for firms' R&D decisions is $\gamma = 0.2$

The time period is considered to be a week, so we are showing approximately 40 years of simulated data well after transitory growth dynamics have died out. Aggregate output exhibits irregular fluctuations and cycles; peak to trough swings in GDP are on the order of 1 to 3 percent. Utility also fluctuates with both output and the evolution of the quality of products produced and consumed, but also grows due to long term net improvements in product quality. These net improvements are driven both directly and indirectly by innovation. Existing firms' product qualities may rise or fall in response to innovations, but also as consumers shift toward higher quality product mixes, less successful firms are driven from the market, and new firms enter.

When the number of firms engaging in R&D increases, spending on R&D increases, driving up output, consumption, and utility.[14] A second effect is that more firms innovate over time, driving the rate of growth of utility upward. Figure 2 below illustrates these level and growth effects on utility (equivalently, quality adjusted output) in a run with the intensity of choice for firms' R&D decisions increased dramatically (from $\gamma = 0.2$ above, to $\gamma = 10$).

[14] In the representative agent case, the multiplier for output is $\frac{1}{\eta-1}$, where η is the markup.

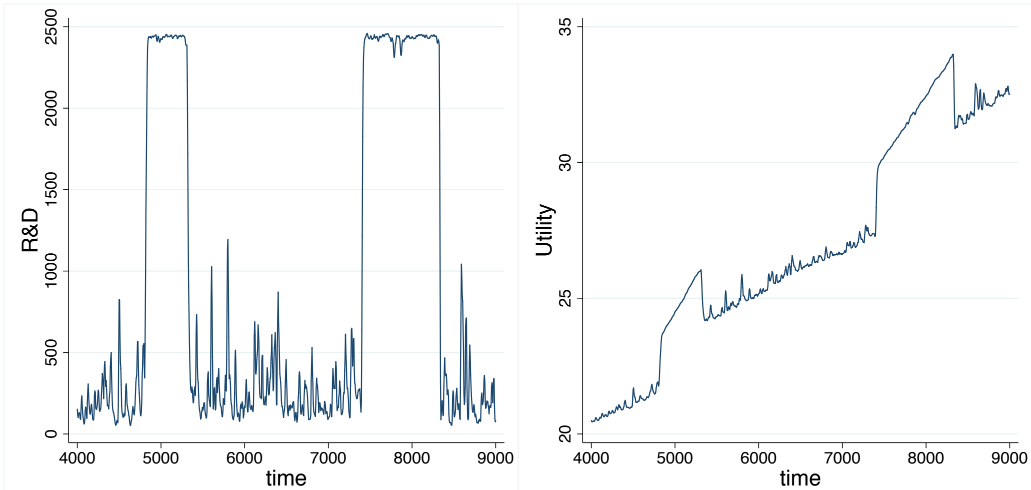

Figure 2: Run similar to that in Figure 1, but with high intensity of choice $\gamma = 10$ for R&D decisions. The number of firms n is 2500.

Here, as the relative profits of firms engaging in R&D evolves, there is strong herding of the population of firms toward and away from engaging in R&D. These shifts lead to shifts in both the level and growth rate of overall consumer utility.

Now consider the distribution of firm sizes as measured by final demand shares. We start the simulations with characteristic magnitudes (z-base$_i$ and z-comp$_{i,j}$) initialized to random sequences of zeros and ones, so that there is idiosyncratic variation in product quality across firms. However, the representative consumer initially sets equal shares across firms. As each simulation proceeds, the consumer searches for better bundles of goods.

If there is neither product nor process innovation, then the optimum bundle for the consumer is static, and demand is redistributed across firms over time, leading to a skewed distribution of demand shares. The degree of skewness is influenced by the CES utility elasticities. Lower values of ρ_1 and ρ_2 indicate a greater taste for variety in characteristics and products, limiting the impact of product quality on market shares. The shape of the distribution is also affected by the ratio $\frac{m}{n}$ of product characteristics to goods, as well as the distribution of complementarities and the entry and exit process. For example, if $\frac{m}{n}$ is small, then there is less room for firms to have independent niches in the product space, and so the market tends to become more concentrated.

Including ongoing product innovation leads to ongoing changes in the relative qualities of goods and so ongoing churning in demand shares. The share distribution follows a similar pattern to that above in early rounds. Starting from a degenerate distribution with all the mass on $1/n$, it first spreads out and then becomes skewed as shares are progressively reallocated among products.

As innovation proceeds, and product churning emerges, the degree of skewness continues to evolve. The ultimate limiting distribution depends on the stochastic process for product innovation in addition to the factors above (ρ_1, ρ_2, $\frac{m}{n}$, the distribution of complementarities, and the entry and exit process).

Figure 3 shows the distribution of product shares and the values of one of the 50 hedonic characteristics (characteristic 10) over the firms at time 20,000 in the run in Figure 1. Here we exclude zero shares and zero characteristic values (held by 374 and 262 of the 1000 firms respectively) and display the distributions of non-zero values.

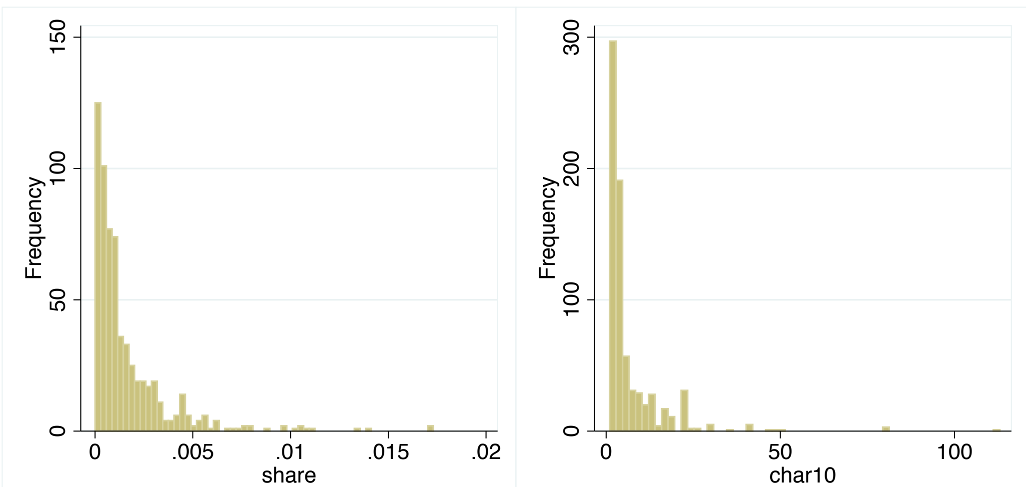

Figure 3a: Distributions of product shares and values of hedonic characteristic 10 by firm at time 20,000 in the run in Figure 1.

11. Conclusion

We have developed an agent-based macroeconomic model in which product innovation is the fundamental driver of growth and business cycle fluctuations. The model builds on a hedonic approach to the product space and product innovation proposed in Georges (2011). Ongoing R&D activities, product innovation, and consumer search yield ongoing firm level and aggregate dynamics. Holding productivity constant, output fluctuates but does not grow in the long run. However, utility, or equivalently quality adjusted output, does exhibit long run endogenous growth as a result of product innovation. The distribution of product market shares tends to become skewed, with the degree of skewness depending on the opportunities for niching in the characteristics space. As the number of firms grows large, business cycle dynamics tend to become dominated by an innovation driven investment cycle.

Appendix: Representative Agent Benchmark

Consider the case in which all firms are identical and each starts with a 1/n share of the total market. Suppose further that all firms engage in R&D in every period and experience identical innovations over time.

In this case, the equal individual market shares will persist, since there is no reason for consumers to switch between firms with identical product qualities and identical prices. Further, there is a unique equilibrium for the real production and sales of consumer goods Y at which demand and supply are in balance. At this equilibrium, aggregate real activity depends on the markup η, the per firm overhead labor costs H and R, the wage rate W (for production workers), labor productivity A (for production workers), and the number of firms n. Specifically, at this equilibrium $Y = (\frac{1}{\eta-1}) \cdot \frac{A}{W} \cdot (H+R) \cdot n$. See below for details. Further, this equilibrium is a steady state of the agent dynamics in the model and is locally stable under those dynamics. If, for example, firms all start with production less than steady state production, then since the markup $\eta > 1$, demand will be greater than production for each firm, and production will converge over time to the steady state equilibrium.

We can see this as follows. Since all firms are identical, they produce identical quantities q of their goods. Then total labor income is:

$$E = n \cdot [\frac{W}{A} \cdot q + H + R]$$

Each firm also charges an identical price p for its good, which is a markup η on marginal cost

$$p = \eta \cdot \text{MC}$$

$$\text{MC} = \frac{W}{A}$$

and so produces and sells

$$q = \frac{E}{n \cdot p}$$

units of its good.

These relationships yield the following steady state equilibrium value for (per firm) production.

$$q^* = \frac{(H+R) \cdot \frac{A}{W}}{\eta - 1}$$

We can see that $\partial q^*/\partial(H+R) > 0$, $\partial q^*/\partial A > 0$, $\partial q^*/\partial W < 0$, and $\partial q^*/\partial \eta < 0$. These are all demand driven. An increase in the cost of overhead labor (H or R) raises the incomes of overhead workers, raising AD and thus equilibrium output. An increase in labor productivity A will cause firms to lower their prices, raising aggregate demand and equilibrium output. Similarly an increase in the wage rate W of production workers or in the mark-up η will cause firms to raise their prices, lowering AD and equilibrium output.

Further, if in this representative agent case firms follow simple one period adaptive expectations for demand, then firm level output dynamics are given by:

$$q_t = \frac{1}{\eta} \cdot q_{t-1} + \frac{1}{\eta} \cdot (H + R) \cdot \frac{A}{W}$$

Thus, given $\eta > 1$, the steady state equilibrium q^* is asymptotically stable.

Total market output in the steady state equilibrium is just

$$\begin{aligned} Y^* &= n \cdot q^* \\ &= \frac{n \cdot (H + R) \cdot \frac{A}{W}}{\eta - 1} \end{aligned}$$

Clearly, this will be constant as long as there is no change in the parameters H, R, A, W, η and n. Growth in the number of firms n or the productivity of production labor A will cause total production to grow over time. Balanced growth in production wages and labor productivity will have no impact on total production, while changes in overhead labor compensation H and R also positively affects equilibrium output.

The effects of A and W on equilibrium output depend on the assumption that the productivity and wages of R&D labor are independent of the productivity and wages of production labor (recall that nominal overhead labor costs $H + R$ are constant). As firms respond to increases in A by lowering price, this raises the real income going to overhead labor and thus raises aggregate demand. The effect is large enough to preserve the employment of production workers ($\frac{n \cdot q}{A}$), which would fall if it were not for the offsetting increase in aggregate demand. Similarly, an increase in the wages W of production labor induces firms to increase prices one for one, leaving real wages unchanged. However, the higher prices erode the real incomes of overhead laborers, reducing aggregate demand, equilibrium output, and the demand for production labor.

Most importantly for the present paper, note that total equilibrium production Y^* is, in this case of identical firms, entirely independent of product quality. Improvements in product quality will, however, increase consumer utility, or equivalently, the quality adjusted value of total production. Specifically, given the nested CES formulation of utility, if the magnitudes of all product characteristics grow at rate g due to innovation, then the growth rate of consumer utility will converge in the long run to g. If the magnitudes of different characteristics grow at different rates, the growth rate of utility will converge to the rate of growth of the fastest growing characteristic. All else equal, the long run growth path of utility will be lower in the latter case than in the former case.

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