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ECONOMICS

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June 2004

NUMBER 48

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This series is registered under
ISSN 1753-2590 (Print)
ISSN 1753-2604 (Online)

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Entry, Competence-Destroying Innovations, Volatility and Growth: Lessons from Different Industries

Mariana Mazzucato*

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Acknowledgements: I thank Boyan Jovanovic and Giovanni Dosi for useful comments on an earlier draft. All errors remain my own. Financial help from the following grant is appreciated: European Commission Key Action 'Improving the socio-economic knowledge base' contract HPSE-CT-2002-00146.

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Abstract

Periods of Schumpetarian creative destruction are well captured by indicators of turbulence that highlight changes in inter-firm variety, such as the market share instability index and relative growth rates. Entry/exit rates do not always serve this purpose. The point is illustrated through the case of the personal computer industry which experienced high entry rates (and high absolute firm growth rates) simultaneously with incremental innovation and relative stability in the market shares of the incumbent firms. The period of radical innovation that occurred in the PC industry after the period of high entry/exit was characterized by large changes in market shares and relative growth rates. Besides market share instability, different indices of stock price volatility (excess volatility and idiosyncratic risk) also prove to successfully capture periods of radical innovation. After developing these points using detailed data for the auto and PC industries, the correlation between innovation and volatility is studied in 34 industries with different levels of innovativeness. The results provide new insights into the dynamics of economic growth driven by General Purpose Technologies (GPTs).

Keywords: radical innovation, market structure, volatility, growth.

I Introduction

Entry and exit patterns, like firm turnover rates, are commonly used to describe and measure industrial turbulence during periods of Schumpetarian creative destruction. Macro studies on the effect of innovation on the reallocation of resources within and between sectors use such data to study the turbulence underlying the reallocation (Caballero and Hammour 2000, Davis and Haltiwanger 1998). Industry life-cycle studies analyze entry and exit patterns and innovation to gain insights on the cause and consequences of the industry 'shakeout', common to the early evolution of many industries (Geroski and Mazzucato 2001, Gort and Klepper 1982, Klepper 1996, Utterback and Suarez 1993). And the organizational ecology literature is interested in the relationship between entry/exit rates (firm density) and the dynamic process by which firms gain 'legitimation', i.e. social acceptance (Carroll and Hannan 2000). In all of these works, periods of high entry are described as periods of creative innovation and volatility often followed by periods of rationalization and stability.

Yet a closer look indicates that those periods in the industry life-cycle which are characterized by the highest rates of entry and exit are not necessarily the most turbulent periods if what we mean by turbulence is the shakeup in industry market structure underlying Schumpeter's notion of creative destruction: '…*the process of industrial mutation…that incessantly revolutionizes the economic structure from within, incessantly destroying the old one, incessantly creating a new one.*' (Schumpeter 1975, p. 83). For example, Mazzucato (2002) illustrates that in the case of the US personal computer industry, although entry and exit rates were highest in the first decade of the industry's evolution (i.e. 1974–1984), firm market shares underwent the most change during the second decade (i.e. 1985–1995). This second decade was the period of radical innovation (Bresnahan and Greenstein 1997). In fact, the market structure of the PC industry, measured both by traditional concentration ratios as well as more dynamic indices used below, hardly underwent any change during the first 10 years when innovation remained incremental and wed to the necessity of being 'IBM compatible'.

The fact that periods of radical innovations coincide with periods of market structure turbulence provides support to the literature on 'competence destroying' innovations where radical or architectural innovations cause inertial incumbents tied to the status quo to lose their lead (Tushman and Anderson 1986; Henderson and Clark 1990)[1]. It also provides support to the emphasis of evolutionary industrial economists on 'distance from mean' dynamics (Dosi and Nelson 1994; Geroski and Mazzucato 2002)[2]. Selection, in the evolutionary perspective, is driven by inter-firm differences (e.g. caused by firm specific

1 Interestingly, recent articles on competence-destroying/enhancing innovations tend (in the opinion of the author) to often pay more attention to the qualities of the innovations than to their effect on market structure, risking to miss the important Schumpetarian point made by the early contributors to this perspective (Tushman and Anderson, 1986; Henderson and Clark 1990).

2 In the theoretical evolutionary literature, distance from mean dynamics are modeled via 'replicator dynamics', where a firm's growth is determined by how different it is from the weighted average in the population (Dosi and Nelson 1994; Mazzucato, 2000).

innovation), so a world of representative agents would be a world without growth/change. This is why evolutionary economists tend to emphasize not absolute growth rates but relative growth rates (or the 'population' perspective), and indices such as the market share instability index (developed below) which embody such relative dynamic changes. The lesson that emerges from the study of innovation and market structure in the personal computer industry is that periods of high entry/exit are not necessarily the same periods in which relative growth rates undergo the most change. The latter tends to occur when radical innovation creates differences between firms, whereas the former can occur even during periods of technological stability.

The paper considers the implication of these points for our ability to 'measure' creative destruction and the insights that this provides for our understanding of micro and macroeconomic growth during periods of radical technological change. Section II focuses on the dynamics of entry/exit, relative growth and innovation during the early history of the auto and computer industries. Section III uses these results to draw insights on useful 'indicators' of industrial and financial volatility that capture periods in which the dynamics of creative destruction cause inter-firm variety to increase. Section IV investigates industrial and financial volatility in a wide cross section of industries with varying levels of innovativeness. Section V considers the implications of the resulting relationship between innovation, inter-firm variety and volatility for the study of economic growth. In particular, it provides new insights into the dynamics of growth driven by General Purpose Technologies (Helpman and Trajtenberg 1998).

II Entry/Exit, Relative Growth and Innovation[3]

Entry and exit patterns in both the automobile industry and the PC industry follow the standard pattern highlighted by industry life-cycle studies (see Klepper 1997 for the case of tires, lasers, TVs, etc.). Figure 1[4] illustrates that in both industries, firm numbers rose very quickly during the first two decades—reaching just under 300 after 15 years, and then began to steadily fall. By 1926 only 33% of the firms that began producing automobiles during the previous 22 years had survived. By 1999 only 20% of the firms that began producing PCs in the previous 22 years had survived. Figure 2 illustrates that fifty percent of the total number of firms in both industries lasted only about 5 years—with many not even making it through their first year.

Faithful to the standard life-cycle story (Jovanovic and MacDonald 1994; Klepper 1996, Utterback and Suarez 1993), in both industries the shakeout began shortly after product

3 The data sources used in the following sections are listed in Appendix A.

4 In Figs 1, 2, 4, and 5, 'industry age' on the horizontal axis begins with the year that the industry began. The US auto industry began in 1899 and by 1926 it had already attained an equal importance to shipbuilding and railroads (Epstein 1928). The PC industry began in 1974 with the introduction of the first mass produced minicomputer, the Altair 8800, produced by Micro Instrumentation and Telemetry Systems (the IBM PC emerged later in 1981).

standardization[5]. In the auto industry the timing of the shakeout coincided with Ford's introduction in 1910 of the industry's first branch assembly plant to produce the first standardized car, the Model T. The extraordinarily high exit rate in 1910 was due to the large fall in demand for high-priced cars that occurred in that year and the fact that those firms not able to adapt to the new standardized cheaper cars (lighter-weight, four cylinder vehicles) were forced to exit (Epstein 1928). In the PC industry most of the exits occurred between 1987–1993, coinciding with two developments which allowed the production of PCs to be standardized and 'commoditized': Intel's introduction of the 32-bit 386 processor in 1985 and Microsoft's introduction of Windows 3.0 in 1990—both of which made consumers care more about what was inside the box than who was the maker of the box (Bresnahan and Greenstein 1997).

The study of innovation dynamics in the two industries reveals that the similarities in entry and exit patterns hide an important qualitative difference between the two industries: whereas the period of high entry rates in the auto industry was also the period of radical technological change, this is not the case in the PC industry. Empirical studies on technological change in the auto industry suggest that the most radical innovations occurred in the very early years, when entry rates were the highest (i.e. before 1925). Abernathy et al. (1986) list all process and product innovations in the auto industry from 1893-1981, weighting them— via a 'transilience' scale— 1 to 7 according to how much they affected the production process: 7s represent radical innovations (e.g. the advent of the assembly line in 1910) and 1s incremental ones (e.g. new paint procedure). During these 88 years, there were only 18 innovations that received a 6 or 7, and nine of these occurred before 1917. After 1940, only four innovations received such high weights. Figure 3, which displays the innovation index over time (the number of product and process innovations multiplied by their weights), illustrates that the intensity of innovation fell over time.

This fall in innovation in the auto industry can also be seen through the 'quality change' index plotted in Figure 4. The index, used in Filson 2001, is computed by dividing BEA price ratios by quality adjusted price ratios (the latter computed for autos through a hedonic price study by Raff and Trajtenberg, 1997; and for computers using a hedonic price study by Berndt and Rappaport, 2000). The index illustrates that the first 10 years in the auto industry witnessed the highest degree of quality change: 25% between 1895–1908, 3.1% between 1909–1922 and 3.2% between 1923–1929. After 1930 the index dropped dramatically.

Unlike the auto industry where most of the price and quality changes occurred in the first decade, most of the price and quality changes in the PC industry occurred in the third decade of its evolution: 34% quality change between 1975–1986, 17% between 1987-1992 and 38% in the period 1993–1999 (Figure 4). This third decade includes the rise of the Intel chip (1987), the rise of Windows (1990), and the commercial rise of the World Wide Web (1995)—all contributing to the loss of IBM's monopolistic control of sales

5 Although there are some differences between the different life-cycle approaches (see Klepper and Simons 1997 for a review), they all emphasize that the shakeout begins with the emergence of a standardized product. One of the main differences between these approaches is the emphasis in Klepper 1996 on increasing returns to R&D that occurs simultaneously with product standardization, a more continuous process than the emphasis in Utterback and Suarez (1993) on a single discontinuous event.

and the innovation process (until then everything had to be 'IBM compatible'). Bresnahan and Greenstein (1997) attribute the higher degree of competitive innovation in this third decade of the PC industry to the 'vertically disintegrated' structure of innovation—spread out between the makers of the PCs (e.g. Dell), the makers of microprocessors (e.g. Intel), the makers of the operating systems (e.g. Microsoft), and the makers of application software (e.g. Lotus). From 1980-1988, innovation in the PC industry was more of the 'competence-enhancing' type: it served to enhance the existing competencies and lead of IBM. From 1989-1996, innovation in the PC industry was of the 'competence-destroying' type: new radical innovations destroyed the lead of IBM.

III Market Volatility: Indicators of Creative Destruction

In both industries, the periods of greatest change in technology were also the periods of greatest market structure instability. Not surprisingly, these were also the periods of lowest market concentration. Yet, as argued elsewhere (Gort 1963), a dynamic understanding of competition requires dynamic indices of competition to replace the standard, and static, concentration ratios. Given the emphasis here on the disruptive effect of radical innovations on market structure, a better measure of competition and market structure is found in a market share instability index which tracks absolute changes in market shares (Hymer and Pashigian 1962):

$$I = \sum_{i=1}^{n} [| s_{it} - s_{i,t-1} |] \tag{1}$$

where s_{it} = the market share of firm i at time t. The higher is I, the more competitive is the industry[6]. This is a more dynamic index because even if the concentration ratio remains high, if the lead of the incumbents does not last long, then the industry is still considered competitive. A similar index is the rank order index, which tracks changes in rankings between firms[7]. Since the summation of market shares must sum to 1, it is also an appropriate index to measure changes in relative growth emphasized by evolutionary economists.

Using this index, Table 1 and Figure 5 indicate that in the auto industry market share instability was highest during the period 1900–1928. This is supported by Figure 6, which illustrates the constantly changing positions of the 28 leading producers during this period (Epstein 1928). From 1940 onwards, market share instability steadily decreased as

6 Although the index might be affected by the number of firms, it is empirically not very sensitive to it because small firms do not contribute greatly to the value of the index. This is because they account for such a small share of the industry and because they tend to grow no faster on average than large firms (Hymer and Pashigian 1962, p. 86). To prevent the changing number of firms to affect this index, *I* is calculated here using only the market shares of the top 10 firms in each industry. In the auto industry, the 10 firms are: Ford, GM, Chrysler, Studebaker, Packard, Hudson, Nash, Willys, Kaiser and American Motors. In the PC industry, the 10 firms are: IBM, NCR, Apple, Hewlett-Packard, Compaq, Dell, Gateway, Toshiba, Wang, and Unisys. In the PC industry, different compositions of top firms were experimented with to ensure that *I* is not sensitive to the particular firms included in the calculation.

7 For a review of these indices, see Gort (1963)

did also innovation and new firm entry. Market share instability temporarily increased in the 1970s, when foreign firms entered the US auto market, but the level was still much lower than that experienced during the industry's early creative stage.

In the PC industry, market share instability rose with the entry of new firms in the 1980's but became especially high in the late 1980's and early 1990's when IBM lost its monopoly of the innovation process (forcing all innovations to be 'IBM compatible'), allowing the new firms—that had entered much earlier—to gain market share and have greater influence over the innovation process. Table 1 indicates that market share instability in the PC industry was highest in the decade 1990–2000. Column 2 indicates that this was not the same period in which *absolute* firm growth was the highest: individual firms and the industry as a whole grew fastest during the decades in which entry rates were highest (1974–1984), but the greatest changes in market shares occurred during the decades with the most radical innovations (Bresnahan and Greenstein 1997).

The fact that in both industries, periods of radical innovation underwent the greatest change in market shares—and that in the case of computers this was not the same period as the period with high entry rates and with high absolute growth rates—supports the literature on 'competence-destroying' innovations which looks at the effect of radical (or architectural) innovations in upsetting market structure. It also supports the emphasis in evolutionary economics, on the importance of understanding the *relative* growth of firms.

The dynamics of entry, innovation and volatility in the computer industry are not unique. Any industry that undergoes a fundamental change in its knowledge base (such as the pharmaceutical industry after the life-science revolution of the mid-1980's) will experience radical innovation at a different moment from the period of early entry and growth. In the PC industry this occurred because the industry emerged from a pre-existing industry (mainframes) and it took a while for the new entrants to be able to shake off the power of the incumbents from that pre-existing industry. The auto industry did not emerge from a pre-existing industry in the same way (the closest industries to the auto industry were those of bicycles and carriages, which is not comparable to the similarity in technology between mainframes and PCs).

Another measure of volatility, besides market share instability, that captures the effect of innovations on market structures is stock price volatility. The relationship between innovation and stock market values operates through the effect of the news on innovation on the expected future cash flows of the firm. As indicated in Pakes' (1985) study of the effect of patents on stock market rates of return:

> '…changes in the stock market value of the firm should reflect (possibly with error) changes in the expected discounted present value of the firm's entire uncertain net cash flow stream. Thus, if an event [a successful patent application] does occur that causes the market to reevaluate the accumulated output of the firm's research laboratories, its full effect on stock market values ought to be recorded immediately.'
>
> (Pakes, 1985, p. 392).

Jovanovic and Greenwood (1999) link stock prices to innovation in a model in which innovation causes new capital to destroy old capital (with a lag). Since it is primarily incumbents who are initially quoted on the stock market, innovations cause the stock market to decline immediately since rational investors with perfect foresight foresee the future damage to old capital. They claim that this explains why the computer stock fell relative to the S&P500 in the 1980's: because the computer firms that were quoted on the market at that time were the incumbents whose capabilities and competencies would be made obsolete by the radical innovations in the 1990's.

In general, when radical innovations upset the existing market structure, this affects the market valuation process due to the effect of market share instability, and the associated uncertainty on the ability of investors to predict future rankings (Mazzucato and Semmler 1999). Mazzucato (2002), which links stock price *volatility* to innovation at the industry level, documents that the periods of greatest market structure instability and innovation in both the auto and PC industries were also the periods of greatest stock price volatility. In fact, both the 'excess volatility' of stock prices, i.e. the degree to which actual stock prices are more volatile than efficient market prices (the present value of discounted future dividends), and 'idiosyncratic risk', i.e. the degree to which firm level stock prices are more volatile than market level (S&P 500) stock prices, were highest precisely during the decades in which innovation was the most radical. The results on excess volatility (measured as in Shiller 1981) in the two industries are illustrated in Figures 7 and 8. In both cases the difference between the standard deviation of efficient market prices (vt*, prices that reflect the present value of future dividends) and actual stock prices (vt) is highest during the periods that the quality change index is highest. The same results concerning idiosyncratic risk are found in Mazzucato and Tancioni (2003). *This suggests that indices of excess volatility and idiosyncratic risk, like the market share instability index discussed above, increase during periods of radical innovation and are thus relevant to the analysis and measurement of creative destruction.*

IV Creative Destruction and Idiosyncratic Risk in 34 Different Industries

Given the relationships described above between industrial and financial turbulence and radical innovation, this section broadens the scope by investigating related dynamics in 34 different industries. We focus on the relationship between innovation and stock price volatility. Specifically, we study whether innovative industries are characterized by more firm level and industry level idiosyncratic risk than less innovative industries. Idiosyncratic risk is defined as the degree to which firm and/or industry level stock returns are more volatile than market level returns. We use different econometric tools to study this question and in each case the null hypothesis is that there is no relation between innovation and volatility.

Like Campbell et al. (2000) we study idiosyncratic risk across different firms and industries. In particular, we study the aggregate behavior of 34 industries and, at the firm level, the evolution of 5 particular industries. We first study quarterly data on industry level stock returns for the period 1976–1997. Later, the analysis is extended to the firm level, employing monthly data for the period 1981–2003 on a selection of firms belonging to the five chosen industries. The last part of the section reports results from a panel estimation of the effect of R&D intensity on the volatility of stock returns.

The 34 industries included in the industry level analysis are listed with their descriptive statistics in Table 1. The 5 different industries for which monthly firm level data is analyzed are:

- Biotechnology (very innovative)
- Pharmaceutical (innovative)
- Computers (innovative)
- Textile (low innovative)
- Agricultural (low innovative)

Using R&D intensity data, the industries are divided into the following three categories: 'very innovative', 'innovative' and 'low innovative'. The categorization is the same as that found in Marsili (2002), based on Pavitt's (1984) sectoral taxonomy of innovatino, illustrated in Table 3.

For both the industry level and firm level data, volatility is analyzed using the following methods: basic descriptive statistics; deterministic and stochastic trend analysis of volatility; Granger causality analysis to see whether the general market returns have predictive capabilities for the innovative industries and firms; variance decomposition analysis to study the relative contributions of unit-specific and unspecific variances to the single units volatilities; and regression analysis with the CAPM model to evaluate the degree to which the average market return explains the industry and firm level returns.

The higher frequency of the data in the firm-level analysis (monthly instead of quarterly) allows us to use GARCH methods to study time varying volatility. Under the ARCH/GARCH model perspective, the variance of the series is directly modeled and the responsiveness to idiosyncratic shocks is evaluated by confronting the dimensions of the AR and MA terms in the variance equation.

Detailed results can be found in the working paper by Mazzucato and Tancioni (2004). Summary results are provided here. Like Campbell et al. (2000) our results using industry level data prove not very interesting: no coherent pattern emerges between innovation and idiosyncratic risk. This is because while some of the innovative industries conform to the predicted behavior (more idiosyncratic risk), other innovative ones do not. The same holds for the low innovative industries. In fact, our expectations seem to be only fulfilled in the extremes of the categorization (e.g. semiconductors on the innovative side). More clear results emerge using firm level data. Here, we find that firms in the most innovative industries (e.g. biotech, computers) do indeed have the highest idiosyncratic risk. And even more importantly, the relationship is strongest during those periods in which innovation is the most radical in these industries. All the different tests used in the firm-level analysis provide significant results concerning the positive relationship between innovation and volatility. Appendix B contains the results from the GARCH analysis.

A simple illustration of the positive results for the innovative industries is depicted in Figures 9–10 (a plot of the moving average of the standard deviation of stock returns in semiconductors and electronic instruments). The degree to which industry specific returns are more volatile than general market returns is highest during the periods (decades) when innovation in these industries has been deemed, by detailed case studies, to be the most radical, i.e. the mid 1980's for semiconductors and the 1990's for electronic instruments (Malerba 1995, Bresnahan and Greenstein 1997).

Given the encouraging results with the firm level data, annual firm-level R&D intensity data is studied, to evaluate whether changes in this variable can explain observed changes in firm level volatility of stock returns. Panel estimation procedures are used to test for the relationship between the volatility of stock returns and R&D intensity (R&D/sales). R&D intensity is a limited proxy due to the fact that R&D represents only the *input* to innovation. A better measure would be patent data as this is a good proxy for innovative *output*. However, we leave this to our work in progress where we connect NBER patent citations data with industrial and financial volatility data.

Employing monthly observations on stock returns, the annual volatility figures are calculated as 12 term (monthly returns) standard deviations. Given the small time dimension of the sample obtained, the preferred estimators are the pooled OLS and GLS, both with the common constant (C) and Fixed Effects (FE) versions. In order to control for the effects of dimensionality on volatility, the firms' relative capitalization weights are also entered in the different specifications. The idiosyncratic elements can thus be captured by the GLS weighting, the FE specification and the relative weights in capitalization. The best results are obtained when the R&D intensity measure is entered with 5-year lags. Table 4 shows the results of the analysis under different specifications.

The hypothesis of a positive relationship between volatility and R&D intensity is not rejected by the data. The innovation effect is statistically meaningful[8]. These results are encouraging and suggest that a more direct consideration of innovation activity, for example using patent data, may improve the results.

The fact that both market share instability and stock price volatility are correlated with periods of radical innovation, suggest that both types of turbulence are related to real production factors. This is important since in both the industrial organization literature and the finance literature, volatility is often discussed in terms of 'random' and/or transient factors. For example, in the applied microeconomics literature, firm growth rates are often modeled as a random walk (Evans 1987)—on their way to the stable equilibrium value— and in the finance literature, stock price volatility is often discussed in terms of 'irrational exuberance' and animal spirits (Shiller 1981). An understanding of how patterns of innovation in both industries are related to different types of turbulence

8 It is interesting to note that the relationship tends to be weakened by considering different firm-specific factors. In particular, jointly controlling for cross-sectional heteroskedasticity via GLS and for Fixed Effects makes the R&D intensity coefficient statistically meaningless. This potentially happens because the covariation between R&D intensity and volatility may be captured by the two sectional corrections (FE and GLS). The same occurs to the coefficient on the weight for capitalization, resulting statistically meaningless only when entered in a FE-GLS specification. The possibility that the joint consideration of both the corrections for the sectional specificities is responsible for this result is also signaled by the fact that the percentage of variance explained by the regression does not improve when moving from a FE OLS to a FE GLS, while the GLS correction resulted highly effective when the a common constant restriction was imposed.

and volatility provides an alternative, *innovation-based*, understanding of volatility and idiosyncratic risk.

We next consider some of the implications of the results obtained thus far for growth theory based on General Purpose Technologies (GPTs).

V Conclusion and Implications for Growth Theory

The paper has argued that micro and macro economists interested in the dynamics of creative destruction can benefit from paying special attention to indicators of turbulence that highlight changes in inter-firm variety. This is because radical innovation often disrupts market structures (Tushman and Anderson 1986), a dynamic not necessarily captured by entry and exit data. It was proposed that a particularly appropriate indicator of the effect of creative destruction on market structures is the market share instability index (Hymer and Pashigian 1962) since it captures changes in inter-firm variety and relative growth rates at the center of the creative destruction dynamic. In fact, in both the case of autos and computers, this index was very high during periods of radical innovation and, in the case of computers, the radical innovation and high instability occurred after the peak in entry rates. The paper also showed that this index tends to co-evolve with indicators of volatility of stock prices (e.g. 'excess volatility' and 'idiosyncratic risk'), suggesting that radical innovation is correlated with turbulence in both stock prices and market shares.

The case of the computer industry is not unique. In the PC industry market share instability was greatest after the period of entry because the industry emerged from a pre-existing related industry (mainframes) in which existing incumbents monopolized innovation in the new industry for the first decade or so (while entry was occurring). In knowledge intensive industries, such as the pharmaceutical industry, this can arise due to the emergence of an external technological event (e.g. the advent of the genomics revolution) which causes radical change in the underlying knowledge base and market structure well after the industry has experienced its early growth stage.

This section considers some implications of the results found in Sections II-IV- for our understanding of the causes and consequences of economic growth during periods of radical change. Recent growth literature has linked TFP growth to the advent of General Purpose Technologies or GPTs (Helpman and Trajtenberg 1998). Some of this literature has focused on the effect that such innovations have on sectoral, cyclical and aggregate volatility (e.g. Caballero and Hammour 2000, Imbs 2002). The underlying assumption in this work is that radical innovations introduced by new entrants lead to increases in firm-level productivity and growth and the summation of the growth of individual firms leads to industry growth (and productivity)[9]. Since innovation causes intra and inter sectoral

9 For example, Imbs (2002) states: 'A direct implication is that the link between sectoral volatility and growth should vary systematically with the sectoral rate of (total factor) productivity. In particular, the higher productivity growth, the higher the positive correlation between growth and volatility'.

reallocation, this also leads to greater volatility in growth rates[10]. When these innovations are GPTs this can lead to economy wide growth and volatility, such as the dynamics experienced during the New Economy years which were driven by the IT revolution (David and Wright 1999, Gordon 2000). Aggregate volatility arises from the fact that the economy is re-adjusting itself to the new technological paradigm. In general, therefore, the literature on Schumpetarian waves and growth predicts a positive correlation between the growth of firms and industries introducing the new technologies, the productivity and volatility of these industries, and the growth, productivity and volatility of the aggregate economy.

The data and arguments provided in Sections II-IV suggest that the logic above may contain some erroneous assumptions. In some situations (e.g. personal computers), the causation is not from changes in absolute firm growth to industry and economy wide growth but instead from changes in relative firm growth to industry volatility to aggregate economic growth. The difference is important since it means that we might not be able to associate periods of aggregate economic growth with periods of individual firm growth. What we might instead observe is a relationship between changes in the relative growth rates of firms (measured directly or also indirectly via the market share instability index), increases in industry level productivity and increases in aggregate economic growth. The connection with economic growth occurs if the industries under question are central to the economy, e.g. industries embodying the new GPT. Given that autos and personal computers were the industries that most embodied the GPTs of the 1920's and 1990's (the proliferation of the internal combustion engine in the 1920s and the combined advances in the microchip and internet technology in the late 1980's/early 1990's) we can use the early history of these industries to test this proposition about growth. The results are found in Table 5.

Table 5 compares the dynamics of autos and PCs (innovation, market share instability, output growth and multi-factor productivity growth-MFP) to that of the general economy (MFP growth and GDP growth). As predicted, in the PC industry, the period in which industry MFP growth was highest was not the same as that when firm and industry growth rates were greatest (firm level absolute and relative growth data can be found in Mazzucato 2003[11]). Productivity grew the most when changes in relative growth rates were highest. This was the same period that aggregate economy MFP and GDP growth was highest (the New Economy period led by IT). It is this fact that provides the most support to our proposition about growth. Furthermore, we see that highest GDP growth occurred precisely during the decades in which quality change and market share instability in both industries was highest. For the years for which MFP data is available (only the early evolution of computers), we see that this is also the period when both industry and economy wide MFP growth was highest. If we calculate simple productivity

10 Caballero and Hammour (2000) argue that productivity growth arises from factors shifting from low to high productivity areas. They also show that most of the increase in productivity occurs from reallocation occurs *within* not between sectors.

11 Mazzucato (2003) proves that changes in firm level relative growth rates co-evolve with the market share instability index.

figures for autos (output over labor input) we get a similar result. Although GDP growth was marginally higher in the period 1923–1929, it is surprising that it was nearly as high in that first decade prior to the mass-production revolution of the 1920's.

The results provide new insights regarding the relationship between firm, sectoral and economy wide growth during Schumpetarian waves. Of course general conclusions cannot be drawn from the study of only two industries. It is important to test these hypotheses on as many different GPT driven industries as possible. Nevertheless, the detailed history of these two particular industries (as well as the more extensive, albeit less qualitative, analysis of the cross section of industries in Section IV), has highlighted the importance of understanding the relationship between innovation, inter-firm variety and volatility in both micro and macro investigations of growth.

Table 1

Standard Deviation (and Mean in Italics) of Market Share Instability, Units and Stock prices

	MS Inst.	**Units**	**Stock**	**Stck/SP500**
AUTO				
1908-1918	**25.2**	**0.1620**	na	na
		0.0401	na	na
1918-1928	22.6	0.1569	**0.1458**	**0.1257**
		0.0304	*0.0939*	*0.0617*
1918-1941	17.9	0.1500	0.1393	.0.1089
		0.0378	*0.0620*	*0.0352*
1948-2000	7.6	0.0638	0.0791	0.0352
		0.0070	*0.0298*	*-0.0020*
1948-1970	10.3	0.0759	0.0671	0.0372
		0.0171	*0.0335*	*0.0002*
1970-2000	5.6	0.0523	0.0881	0.0335
		-0.0030	*0.0243*	*-0.0036*
PC				
1970-1980	1.4	**0.2062**	0.0708	0.0294
		0.2431	*-0.0047*	*-0.0039*
1980-1990	11.5	0.1884	0.0662	0.0324
		0.1450	*0.0154*	*-0.0136*
1990-2000	**17.9**	0.0357	**0.1196**	**0.0445**
		0.0646	*0.0585*	*-0.0003*
1970-2000	28.9	0.1758	0.0905	0.0349
		0.1504	*0.0258*	*-0.0038*

Top=standard deviation, bottom italics=mean value

Bold number=decade with highest value

MS Inst.=instability index from Eq. (1)

Units=units produced

Stock=industry-level stock price

Stck/SP500=industry-level stock price divided by S&P500 stock price

na=not available since auto industry first publicly quoted in 1918

Table 2

Industry level stock returns: descriptive statistics

Industry	Mean	Maximum	Minimum	Std. Dev.	Industry	Mean	Maximum	Minimum	Std. Dev.
TRANSPORT	0.1007	3.4089	-0.2685	0.3831	FOREST PROD. PUBL.	0.0690	0.3300	-0.2166	0.1074
SEMICONDUCTORS	0.0768	1.6463	-0.6776	0.2619	HOSPITAL SUPPLIES	0.0529	0.2607	-0.1699	0.1064
NAT. GAS PIPELINES	0.0798	0.9588	-0.3777	0.1502	INSURANCE MULTIL.	0.0669	0.2992	-0.2170	0.1053
BUILD. MATERIALS	0.0674	0.4662	-0.2613	0.1367	FINANCIAL	0.0705	0.3073	-0.2450	0.1041
ELECTRONIC INSTR.	0.0480	0.5427	-0.2612	0.1367	FOOD CHAINS RETAIL	0.0724	0.3119	-0.1619	0.1014
AUTOMOBILES	0.0782	0.4403	-0.2328	0.1331	INSURANCE PROPERTY	0.0752	0.2985	-0.1443	0.1012
TRUCKER TRANSP.	0.0416	0.3759	-0.2406	0.1275	FOREST PROD. PAPER	0.0599	0.3327	-0.1864	0.1001
BANKS NY	0.0816	0.3975	-0.2884	0.1251	CHEMICALS AND COAL	0.0684	0.3070	-0.1955	0.0992
DEPT. STORE RETAIL	0.0666	0.4930	-0.3635	0.1250	INTEGR. DOMESTICS	0.0678	0.3539	-0.2083	0.0950
AEROSP. DEFENCE	0.0736	0.5037	-0.3964	0.1246	METAL AND GLASS CONF.	0.0676	0.2514	-0.2093	0.0946
PAPER CONFECT	0.0646	0.4118	-0.2364	0.1210	BREWERS AND ALCOOL	0.0573	0.2766	-0.1325	0.0940
ENTERTAINMENT	0.0584	0.3630	-0.2835	0.1196	SOFT DRINKS NON ALC.	0.0758	0.2685	-0.1836	0.0926
ALLUMINIUM	0.0593	0.4188	-0.2328	0.1193	ELECRICAL EQUIPMENT	0.0643	0.2536	-0.2529	0.0870
TOBACCO	0.0930	0.3754	-0.2496	0.1177	COMPOSIT OIL	0.0790	0.2893	-0.1575	0.0800
RETAIL COMP.	0.0523	0.2879	-0.3449	0.1145	ELECTRIC POWER COMP.	0.0992	0.3333	-0.0794	0.0740
PUBLISHING NEWSP.	0.0629	0.4078	-0.2308	0.1128	SP500	0.0657	0.2390	-0.2049	0.0713
RESTAURANTS	0.0525	0.2843	-0.2503	0.1081	PUBLIC UTILITIES	0.0930	0.2724	-0.0650	0.0684

Table 3

Intensity of R&D expenditure by sector: time average 1980-1992

	INDUSTRY	**R&D**
HIGH	Aerospace	18.9
	Computers	15.5
	Pharmaceuticals	11.3
	Electronics and telecoms	10.8
	Other transport	8.1
	Instruments	7.2
MED-HIGH	Motor vehicles	4.4
	Chemicals	2.8
	Electrical Machinery	2.7
MEDIUM	Non-electrical machinery	1.7
	Other manufacturing	1.3
	Petroleum	1.3
	Building materials	1.2
	Rubber and plastics	1.2
	Non-ferrous metals	0.8
	Metal products	0.6
	Ferrous metals	0.5
MED-LOW	Paper and printing	0.3
	Food and Tobacco	0.3
	Wood and wood products	0.2
	Textiles	0.2
	TOTAL MANUFACTURING	3.1

source: Table 6.2 Marsili (2001)

Table 4

Panel estimation of the relationship between volatility and R&D intensity in 34 firms from 5 industries (biotechnology, pharmaceuticals, computers, agriculture, textiles)

Method	Dim. corr.	int coeff	t-stat	dim coeff	t-stat	r&d coeff (-5)	t-stat	Rbar sq
Pooled OLS	n	0.106	23.586	-	-	0.056	5.098	0.055
GLS	n	0.086	34.856	-	-	0.048	3.032	0.143
FE Pooled OLS	n	CS spec	-	-	-	0.023	2.354	0.399
FE GLS	n	CS spec	-	-	-	0.017	0.907	0.395
Pooled OLS	y	0.116	22.672	-0.061	-3.897	0.056	5.264	0.085
GLS	y	0.091	29.611	-0.015	-2.187	0.049	3.130	0.167
FE Pooled OLS	y	CS spec	-	-0.090	-1.007	0.023	2.351	0.399
FE GLS	y	CS spec	-	-0.065	-1.659	0.018	0.957	0.401
Pooled OLS	y CS spec	0.205	19.351	CS spec	-	0.038	3.689	0.311
GLS	y CS spec	0.124	16.181	CS spec	-	0.037	2.207	0.291

Note: CS spec = Cross Section specific

Table 5

Growth: Industry (Autos and PCs) vs. Aggregate Economy

	AUTO				*ECONOMY*	
	QUAL. CH.	MS INS	OUTPUT	MFP	*MFP*	*GDP*
1895-1908	**0.2500**	**0.2000**	**0.1356**	na	*na*	***0.0431***
1909-1922	0.0310	0.1800	0.0304	na	*na*	*0.0312*
1923-1929	0.0320	0.1600	0.0378	na	*na*	***0.0455***

	PC				*ECONOMY*	
	QUAL. CH	MS INS	OUTPUT	MFP	*MFP*	*GDP*
1975-1986	0.3400	0.0340	**0.2431**	0.2142	*0.0892*	*0.0313*
1987-1992	0.1700	0.1150	0.0357	0.2800	*0.0500*	*0.0257*
1993-2000	**0.3800**	**0.2010**	0.0217	**0.6388**	***0.1050***	***0.0373***

notes: QUAL. CH. = quality change index, hedonic prices/actual BEA prices, (Filson 2002)
MS INS= market share instability index, (Hymer and Pashigian 1962)
OUTPUT=average growth of industry output (number of cars and PCs)
MFP=average growth rate of multi-factor productivity
GDP= average growth rate of GDP

Figure 1

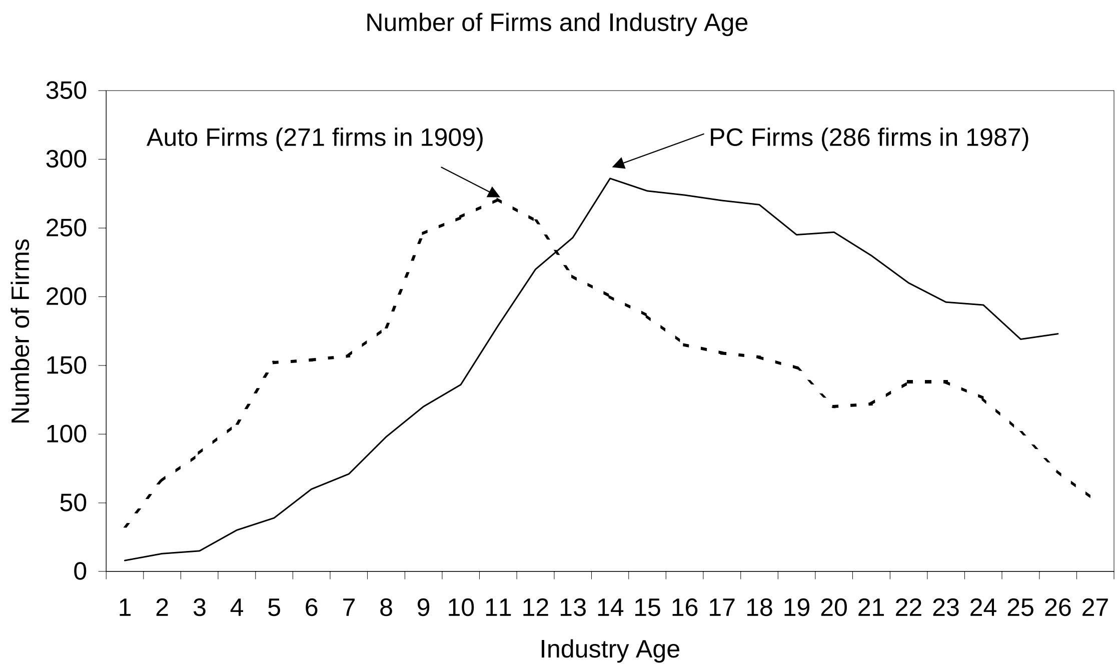

Number of Firms and Industry Age
Auto Firms (271 firms in 1909)
PC Firms (286 firms in 1987)
Number of Firms
0
50
100
150
200
250
300
350
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Industry Age

Figure 2

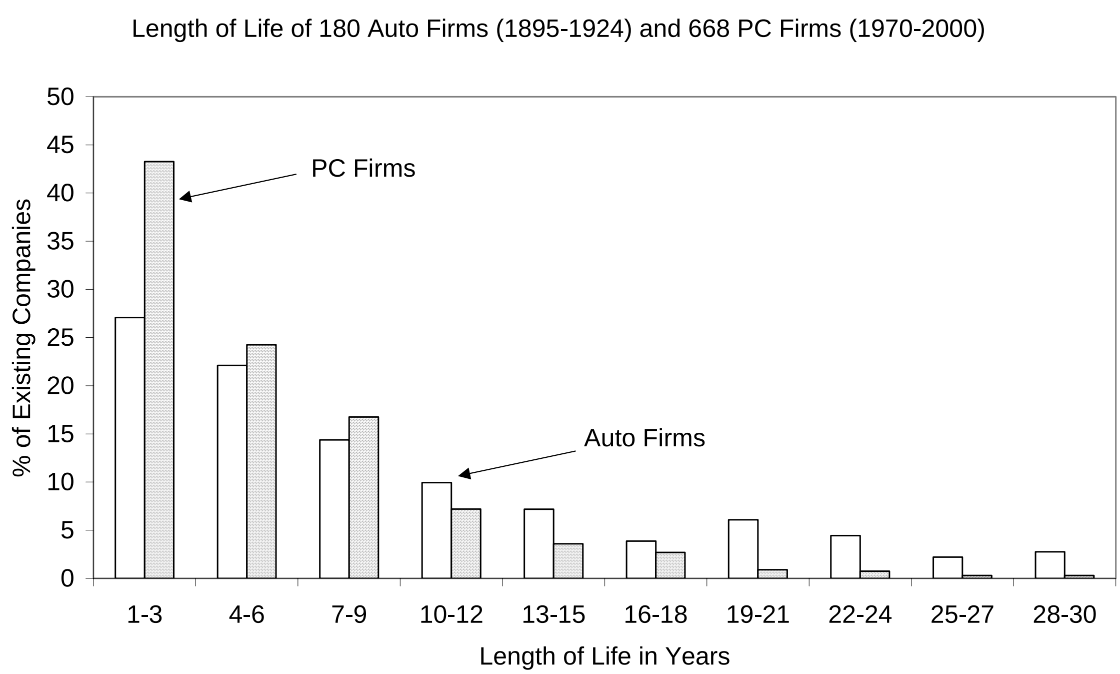

Length of Life of 180 Auto Firms (1895-1924) and 668 PC Firms (1970-2000)
PC Firms
Auto Firms
% of Existing Companies
0
5
10
15
20
25
30
35
40
45
50
1-3
4-6
7-9
10-12
13-15
16-18
19-21
22-24
25-27
28-30
Length of Life in Years

Figure 3

Product and process innovations (transilience weighted) in the US auto industry (3 yr. mov. avg.)

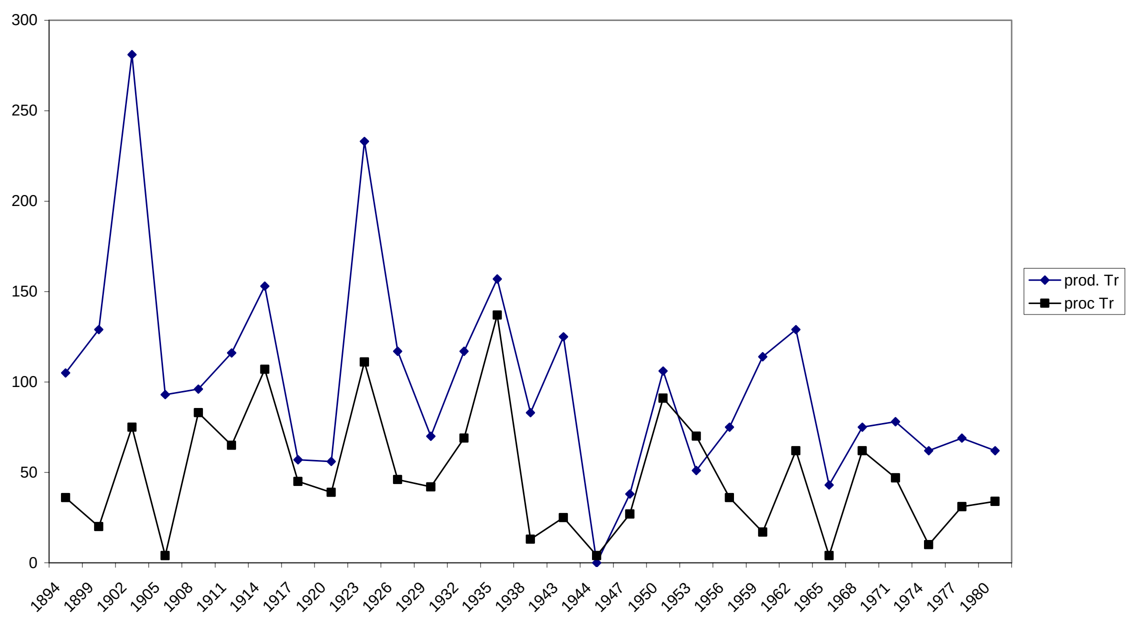


Figure 4

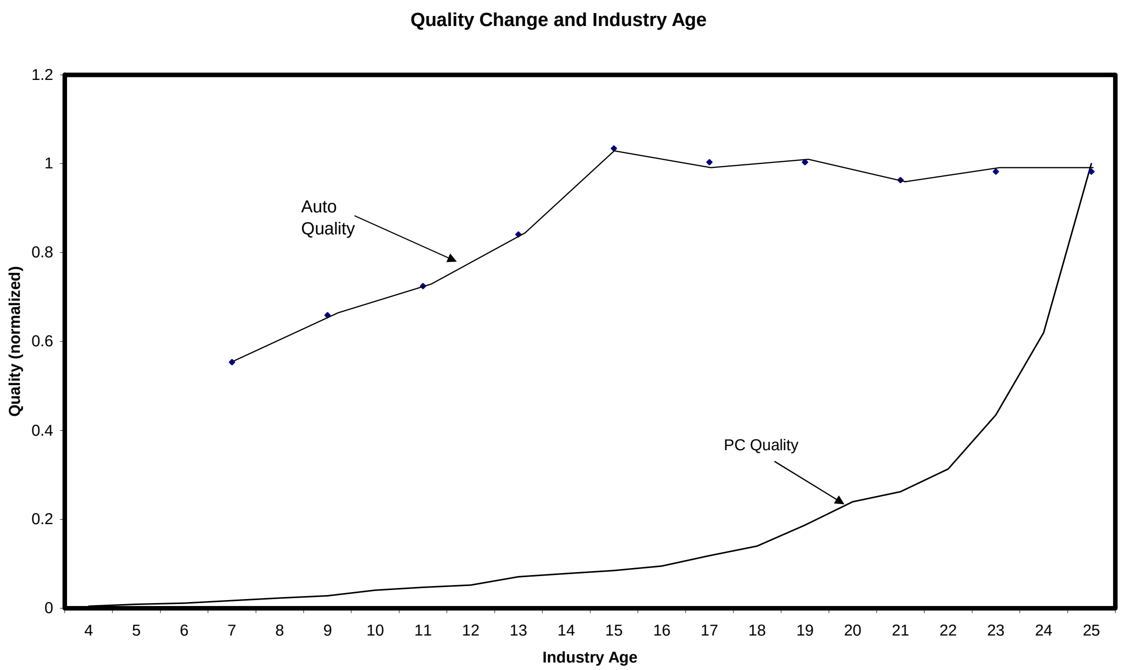

Quality Change and Industry Age
Auto
Quality
PC Quality
Quality (normalized)
Industry Age
0
0.2
0.4
0.6
0.8
1
1.2
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

Figure 5

Market Share Instability and Industry Age

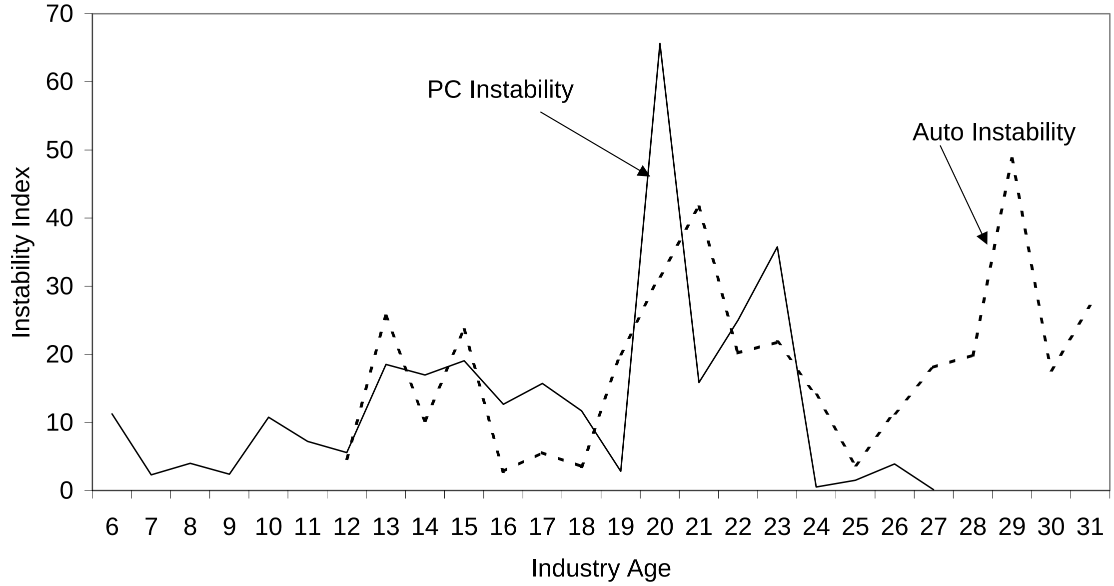


Figure 6

Movement of 28 Leading Auto Producers Ranked According to Places in Production (source: Harvard Business Review, Epstein, 1928)

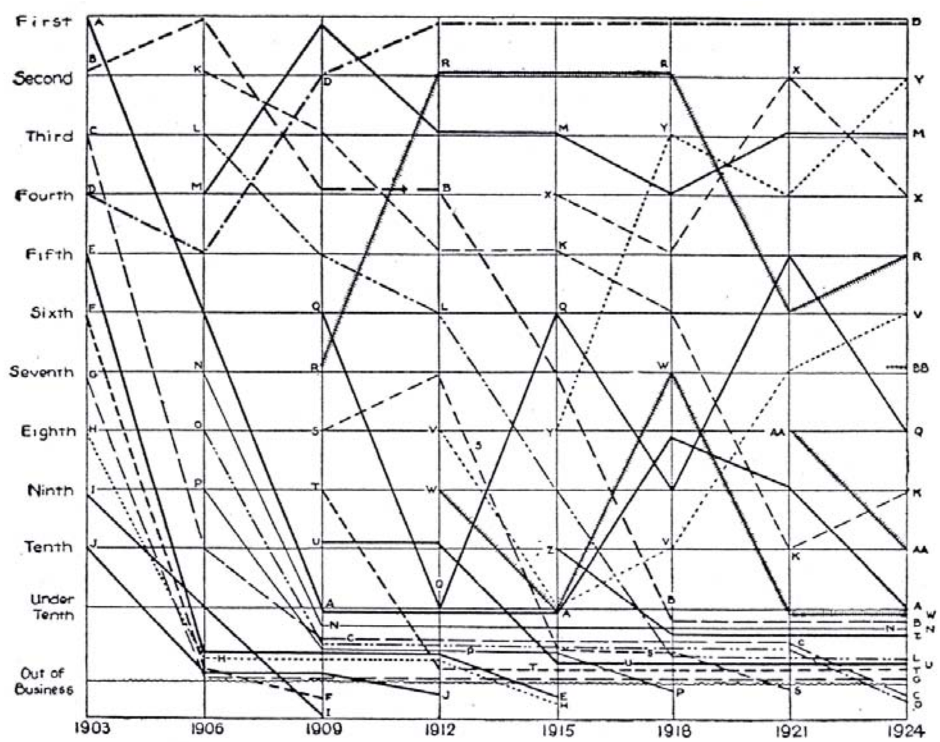


Figure 7

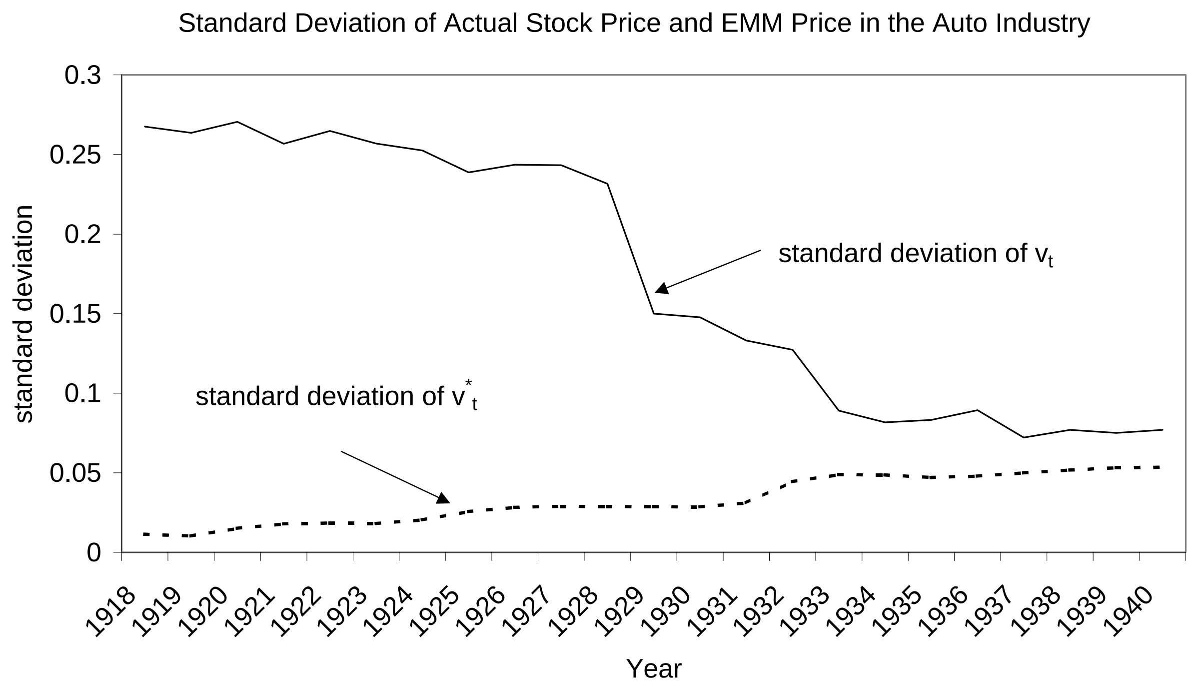


Figure 8

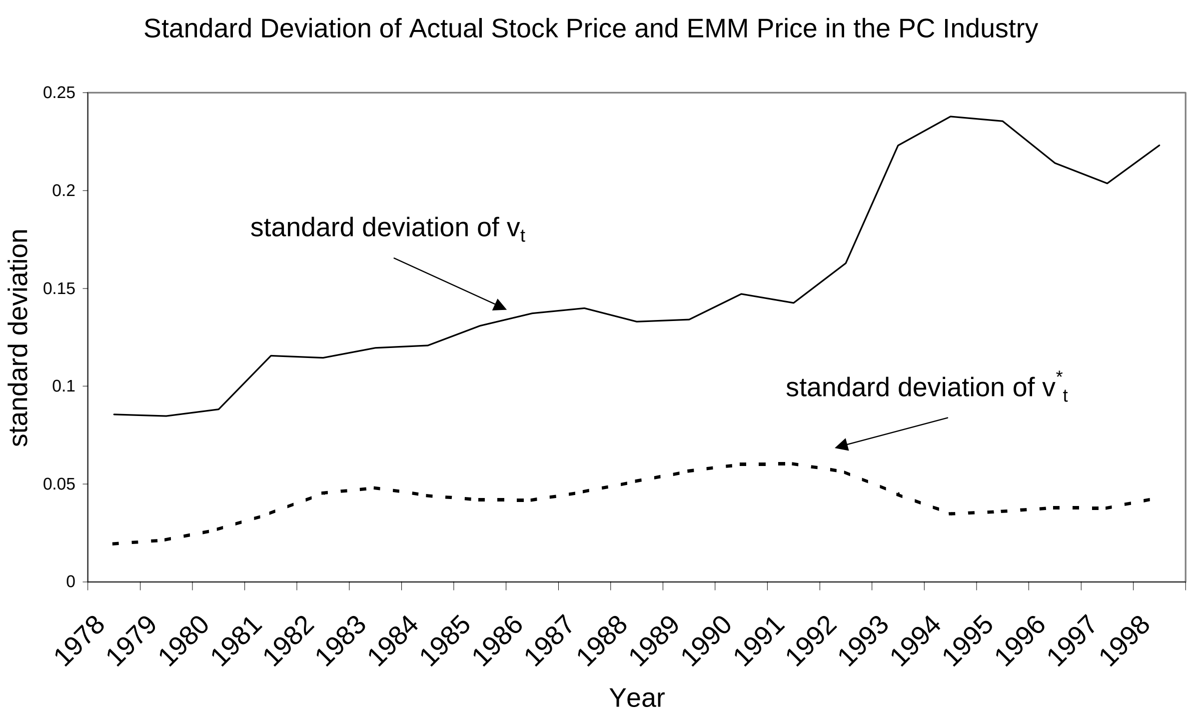


Figure 9

Volatility of Stock Returns in Electronic Instruments vs. S&P 500

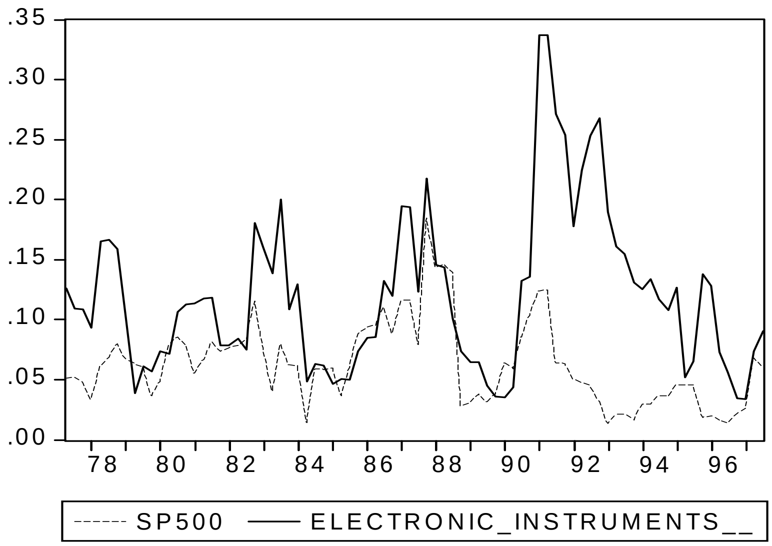
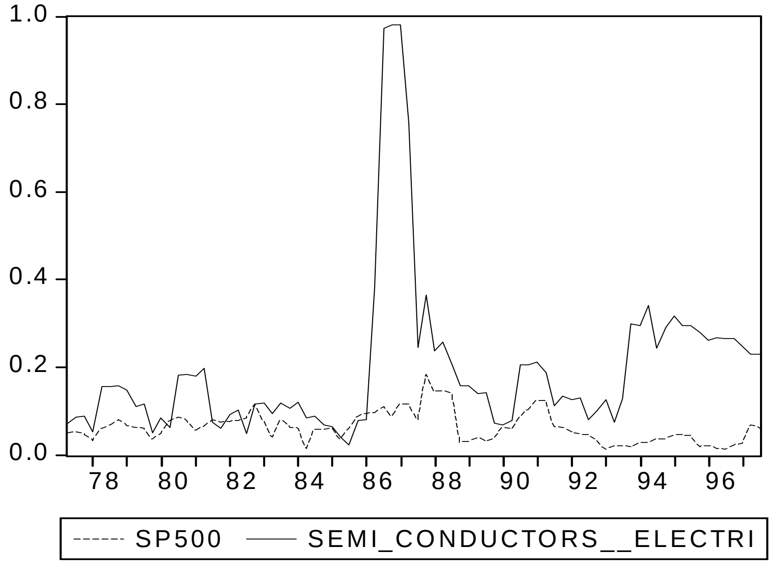


Figure 10

Volatility of Stock Returns in Semiconductors vs. S&P 500



Appendix A: Data Sources

Automobiles: Individual firm units and total industry units from 1904-1999 were collected from annual editions of Wards Automotive Yearbooks (first editions, reporting data starting in 1904, are published in 1924). Although firm-level units were collected for only 8 domestic firms and 5 foreign firms (the first foreign firms entered in 1965), the total industry sales include the units shipped by all existing firms (e.g. in 1909 that includes the output of 271 firms). Firm-specific stock prices, dividends, and earnings/share figures were collected from annual editions of Moody's Industrial Manual. Industry-specific per share data was collected from the Standard and Poor's Analyst Handbook12 (the firms included to calculate that index are listed in endnote V). Hedonic prices and data on changes in quality are from the series used in Raff and Trajtenberg (1997).

Personal Computers: Annual firm-level data on the total number of personal computers produced from 1973-2000 was obtained from the International Data Corporation (IDC), a market research firm in Framingham, Massachusetts. Firm-level stock price, dividend, and earnings per share data were obtained from Compustat. Industry-level financial variables were obtained, as for the post-war auto industry, from the Standard and Poor's Analyst's Handbook (2000). The firms which define this index (listed in endnote VI are all included in the firm-level analysis, except for Silicon Graphics and Sun Microsystems (the only two firms in the S&P computer index which don't produce personal computers)13. Hedonic prices and data on changes in quality are from the series used in Berndt and Rappaport (2000) and Filson (2001).

12 The firms used to create the S&P index for automobiles are (dates in parentheses are the beginning and end dates): Chrysler (12-18-25), Ford Motor (8-29-56), General Motors (1-2-18), American Motors (5-5-54 to 8-5-87), Auburn Automobile (12-31-25 to 5-4-38), Chandler-Cleveland (1-2-18 to 12-28-25), Hudson Motor Car (12-31-25 to 4-28-54), Hupp Motor Car (1-2-18 to 1-17-40), Nash-Kelvinator Corp (12-31-25 to 4-28-54), Packard Motor Car (1-7-20 to 9-29-54), Pierce-Arrow (1-2-18 to 12-28-25), Reo Motor Car (12-31-25 to 1-17-40), Studebaker Corp. (10-6-54 to 4-22-64), White Motor (1-2-18 to 11-2-32), and Willy's Overland (1-2-18 to 3-29-33).

13 The computer industry was first labeled by S&P as *Computer Systems* and then in 1996 changed to *Computer Hardware*. Firms included in this index are:

Apple Computer (4-11-84), COMPAQ Computer (2-4-88), Dell Computer (9-5-96), Gateway, Inc. (4-24-98), Hewlett-Packard (6-4-95), IBM (1-12-19), Silicon Graphics (1-17-95), and Sun Microsystems (8-19-92).

Economy: GDP data and industry and aggregate MFP data was obtained from the BLS (http://www.bea.gov/).

Appendix B: G/ARCH Analysis from Section IV

We approach the question of excess returns and volatility using a CAPM excess returns representation, allowing for a direct formulation and estimation of the variance equation in the context of the ARCH methodology (Engle et al. 1987): We employ as a general starting point the Threshold ARCH-in-mean GARCH-in-volatility formulation of order (p, q):

$$y_t = \mu + \beta x_t + \lambda \sigma_t^2 + \varepsilon_t \qquad (2)$$

$$\sigma_t^2 = \omega + \sum_{i=1}^{p} \delta_i \varepsilon_{t-1}^2 + \psi_{t-1} \gamma \varepsilon_{t-1}^2 + \sum_{j=1}^{q} \phi_j \sigma_{t-1}^2 \qquad (3)$$

where y_t is the firm-level stock rate of return, x_t is the general market rate of return (hence, β is the generalisation of the CAPM to the G/ARCH formulation), and λ is a coefficient linking returns to volatility. The term $\delta \varepsilon_{t-1}^2$ in the variance equation is the ARCH term (equivalent to a MA term) and $\phi \sigma_{1-t}^2$ its generalization to lagged variance (often defined GARCH, an AR term). The term $\psi_{t-1} \gamma \varepsilon_{t-1}^2$ controls for asymmetric effects, in fact $\psi_t = 1,0$ is a wildcard operating according to the thresholds $\varepsilon_t < 0, \varepsilon_t \geq 0$ respectively[14]. The system (2)-(3) is a highly general mean-variance formulation, since it can account for a number of specificities in the data.

In the GARCH analysis, other things equal, the conditional volatility is expected to be bigger in those firms displaying higher innovative efforts. We expect to find higher and meaningful coefficients for the MA term values of the highly innovative firms and bigger defensiveness coefficients (on the AR term) for the low innovative industries. Firms in the low innovation industries do not show meaningful asymmetries in the volatility behaviors. Important asymmetric responses are instead found for most of the innovative industries, particularly for those with the smaller dimensions or the higher innovative

14 Jointly with the mean equation in, this formulation is known as the Threshold GARCH model (Zakoian, 1990).

activity. Although the mean/variance relationship is not industry specific, it is found meaningful in particular for the smallest firms in each industry. In the biotechnology and pharmaceutical industries, these firms are also the most innovative.

The ARCH (responsiveness) parameter is particularly high in the computer and biotechnology industries (the ARCH component should be evaluated contextually with its asymmetric component). The GARCH (variance memory) component tends to be smaller for the firms that have a larger responsiveness to volatility as expressed by the ARCH coefficient. This is what we expected to find, given that GARCH signals for variance smoothness. When we add a dimensionality measure (the ratio of the individual firm capital to industry capitalization), in the variance equation, our results are even stronger. The ARCH component is meaningless for all the TGARCH of the firms belonging to low innovation industries while meaningful results are found for all the firms belonging to the more innovative industries.

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