Technology Adoption, Bubbles and Productivity

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Abstract

In this paper we study the impact of uncertain innovation on the concomitant time path of stock market valuations and technology adoption. We specify the conditions which may produce valuation and adoption profiles often associated with market 'bubbles'. The paper evaluates post bubble production and productivity in a setting which incorporates network externalities. When externality forces are weak, a 'bubbly' profile will most likely entail over-adoption and wasted resources. However, if a significant innovation is prone to positive network effects it is probable that the 'bubbly' process boosts post bubble growth and productivity. Uncertainty and externalities may amplify market valuations as well as adoption. We evaluate the probability that such a 'bubbly' process contributes to overall long term productivity under various scenarios. The paper compares the qualitative results of the model to the Internet bubble and its aftermath and provides a possible explanation for the path of valuation, adoption and productivity during the period. We reason that the boom and bust cycle ending in 2000 may have not been caused by irrational exuberance but rather by expectations for an uncertain technology change, enhanced by inherent network externalities. We also claim that the magnitude of post bubble US productivity growth, which is higher than any seen in 40 years, may have actually been amplified as a result of the preceding boom and bust pattern.

JEL: N1, O14, O30, O40, E32, L1

Keywords: Bubbles, Innovation, Technology Adoption, Network Externalities, Productivity, Decision under Uncertainty

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I. Introduction

US Productivity acceleration following the collapse of the Internet bubble has become the subject of recent debate and research. Non farm productivity growth from 2001 through 2005 has accelerated to over 3.3% per annum, a record increase in over 40 years. Updated MFP data shows unprecedented acceleration to a three year average of 1.9% annually. The fact that such productivity increase occurred following the violent boom and bust cycle of the Internet bubble, is seen by many as a puzzle.

In this paper we study the impact of uncertain innovation on the concomitant time path of stock market valuations, technology adoption and productivity. We evaluate the interaction between uncertain technology change, rate of adoption and network externalities, and specify the conditions which may produce valuation and adoption profiles often associated with market "bubbles". Under our proposed framework the existence of a stock market 'bubble' which coincides with the adoption of a new successful technology is actually a probable event, not an unexpected display of 'irrational exuberance' as is often cited. When externality forces are weak, the most probable outcome of a "bubbly path" includes over adoption and wasted resources. However; we show that if a significant innovation is prone to network effects it is probable that the "bubbly" process generates post bubble superior growth and productivity. Externalities may amplify market valuations as well as adoption, which in turn impact long term productivity. We evaluate post bubble outcome while accounting for the wasted resources and allocation shift induced by the bubble. Could it be that the events of the internet bubble were partially responsible for the magnitude of the post bubble acceleration in productivity?

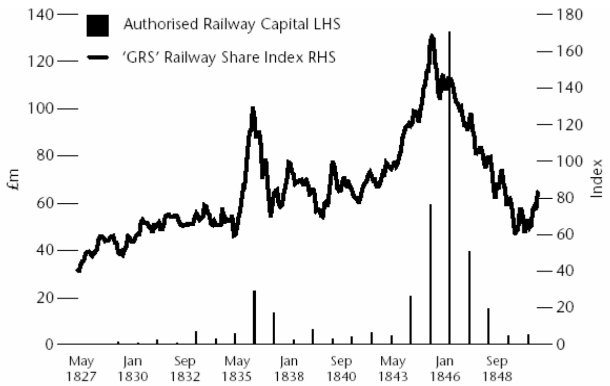
We formulate a non explicit model and identify features which are expected to induce technology adoption and valuation profiles often associated with market "bubbles". We illustrate model implications with the help of explicit simulations and compare results with stylized data pertaining to the internet bubble.

We believe our framework may provide an explanation to the path and outcome of some of the most notable technology related bubbles, including the turn of the century internet frenzy and the railway bubble of 19th century England. The model also provides a parsimonious explanation to the timing and extended duration of the "unexpected" US productivity uplift which followed the collapse of the internet bubble, a widely discussed puzzle in recent literature.

The remainder of this paper is organized as follows: Section II outlines the motivation for our research and includes stylized facts regarding post bubble outcome for both the internet bubble and the English railway bubble of the 19th century. Section III provides a literature overview and a comparative preview of our model. Section IV describes the model as well as the conditions impacting the adoption profile. This section also introduces externalities into our framework. Section V evaluates the stock market path as well as the success rate of individual firms. Section VI evaluates post 'bubble' production and productivity and section VII concludes.

II. Background and Motivation

In order to broaden the motivation for our research we first look back at the British Railroad bubbles of the 19th century. Figure 1 depicts the spectacular rise of the railway share index as well as the growth in authorized railway capital. England was the first economy to massively implement railway technology, and as such coped with inherent uncertainty regarding the economic implications and business rewards associated with such a network of railways. The scale of the task and its potential impact on economy were significant, authorized capital for railway companies in 1846 was in the vicinity of 30% of GDP.



Sources: Authorised railway capital: A.D. Gayer, W. W. Rostow and A. J. Schwartz, *The Growth and Fluctuation of the British Economy 1790–1850*, vol. I, Oxford University Press, 1953, p. 437; share prices: see Annex to Chapter 5.

The Railway Bubbles – England Mid 19th century
Figure 1

The adoption rate as well as the direct impact of the railway bubble on sector activity may be evidenced by the railway mileage data presented in table 1. The most significant impact occurs after the bubble has subsided. The peak of the railway bubble occurred in mid 1845, that year only 144 miles of new rail were opened, the following year, in conjunction with the rapid deflation of the bubble 293 new miles of track were opened. However the process was already in motion, after the bubble deflated: 909 miles and 1400 miles of track were opened during 1848 and 1849 respectively. These tracks, designed and financed during the bubble, were being installed at a period when the valuation of railway shares has already retreated.

Table 13 **Railway shares and railway development in the 'large' railway mania, 1842–9**

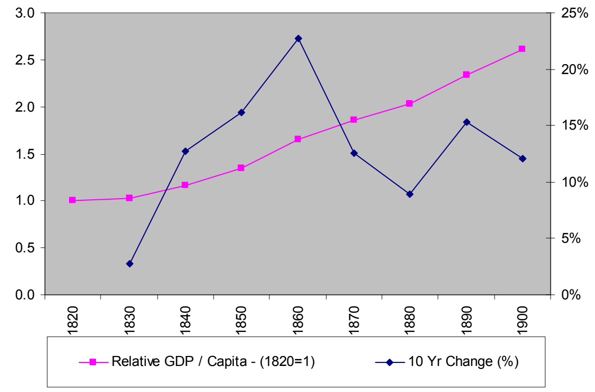
Year	*Authorising Acts**			*Capital authorised £m**	*Mileage opened: annually†*	*Mileage opened: annually† (cumulative)*
	New	*Extensions & completion of existing lines*	*Total*			
1842	4	18	22	5.3		1,939
1843	5	19	24	3.9	105	2,044
1844	26	22	48	20.5	144	2,148
1845	76	44	120	59.5	293	2,441
1846	225	45	270	132.6	595	3,036
1847	115	75	190	39.5	909	3,945
1848	28	57	85	15.3	1,400	5,345
1849	–	34	34	3.9	687	6,032

Sources: *A. D. Gayer, W. W. Rostow & A. J. Schwartz, *The Growth and Fluctuation of the British Economy 1790–1850*, vol. I, Oxford University Press, 1953, p. 316. Reprinted by permission of the Oxford University Press. †B. R. Mitchell, *British Historical Statistics*, Cambridge University Press, 1988, 'Transport and Communications', Table 5, p. 541.

Table 1

The immediate impact of the big railway bubble

Temporary financial crisis followed the collapse of the railway bubble, but apparently this was not the only outcome of the episode. By 1850, over 6000 miles of track were in operation. Track density in England was 7 times that of France or Germany. This spectacular achievement was accomplished without any significant government funding or intervention. As can be seen in Figure 2, GDP per capita during the 1840s, the decade of the bubbles, increased by 16% while the GDP/Capita for the following decade increased by almost 23% the highest GDP decade increase throughout the 19th century. Obviously, we do not claim that railway technology and it's associated financial and technology changes were the sole cause for GDP growth, we merely wish to shed light on the possible net positive effects of a technology focused stock market boom which supports extensive adoption and utilization of new technologies. Even scholars which are skeptic regarding the impact of steam and railway technology on the British economy show that the end of the 1840's were a turning point in productivity figures. Crafts (2004) shows that the contribution of railways to total GDP productivity for the period 1850-1870 was 0.25% annually, a significant increase from the 0.16% contribution just a decade before. Crafts also points out that TFP for the railways sector following 1850 jumped almost two-fold from 1.9% to 3.5%. Acceleration was also documented in other related technologies and markets such as iron processing, steam engine technology, time management techniques and large scale project management methodologies; all of which further supported an increase in GDP per capita throughout the 1850s.



Relative GDP/Capita - England 19th century
Figure 2

One can notice many similarities between the railway bubbles of the mid 19th century and the internet and communication bubble of the 1990's. Both of these boom and bust cycles were focused on innovative new technologies which incorporated significant uncertainty as well as inherent positive network externalities. Both were focused on a specific set of companies and both induced massive targeted investments over a relatively short period.

We view the unprecedented technology change as the primary cause of the financial episodes which followed. In turn we also propose that the bubbly episodes themselves acted as an enhancing mechanism which affected the overwhelming adoption and overall spectacular success of the underlying innovation. Obviously other supporting factors must exist for such a financial process to develop. Favorable interest rates, a relatively stable economic environment, as well as supportive press and information distribution play a significant role (see Shiller (2000) for an overview), however this paper shall focus on technology change and network externalities as the primary driver of events.

This paper sets the spotlight on on uncertain technology innovation, however the framework presented may be applied to other bubbly episodes. Characteristics and outcome of historic bubbles vary significantly but we believe that increased uncertainty regarding a future change associated with the underlying productive assets was a vital contributor to many if not all of the historically significant bubbles. The change causing the bubble need not be technology based. For example, the South Sea and the Mississippi bubbles of the early 18th century were not technology related, however both were initially associated with new world trade opportunities, opportunities which were very difficult to predict and quantify.

In the case of the internet and communication bubble we hypothesize that the deflation of the financial bubble coincided with the beginning of wide spread implementation of this new set of productive technologies which in turn produced information regarding the actual growth rate of this new technology. A reduction in the variance of future growth may be sufficient, under certain circumstances, to induce a valuation tumble even if the technology expectations were rational. To support this claim we shall now return to some stylized facts evaluating the timing of US productivity changes. Table 2 details US non farm business labor productivity growth averages while Table 3 details Multi Factor Productivity changes, compiled from updated data provided by the US Bureau of Labor Statistics. We include labor productivity data as part of our analysis as technology change is in many cases a primary enabler for increased investments in productive asset over time. Thus, in the spirit of Domar (1961) when we decompose the productivity contribution we could be underestimating the contribution of technology change to overall productivity.

Table 2	
US Non Farm Labor Productivity / Hour 1948 - 2005 Average Annual Change (%)	
1948 - 2005	2.29
1948 - 1982	2.28
1983 - 1994	1.94
1995 - 2000	2.18
1995 - 1997	1.60
1998 - 2000	2.77
2001 - 2005	3.32

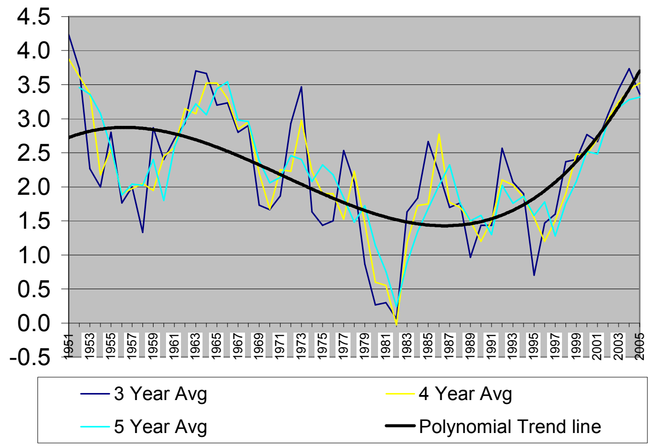
Source: U.S. Department of Labor, Bureau of Labor Statistics

Table 2 clearly shows an increase in productivity per hour during the period following 1997. During the heat of the stock market boom (1998-2000) this average productivity change was higher by 0.5% per annum. Evaluating productivity over the full term of the stock market bubble, from 1995 to 2000, shows productivity change in line with long term averages. The most dramatic productivity growth is evident after the stock market boom had collapsed in 2000. In the period 2001- 2005 average annual productivity change accelerated to over 3.3%, more than a 1% average annual increase over long term averages, and a 1.5% over the pre boom average since 1983. The MFP data detailed in Table 3 is even more striking with a post bubble average annual increase of 1.9%; three times higher than the pre bubble period.

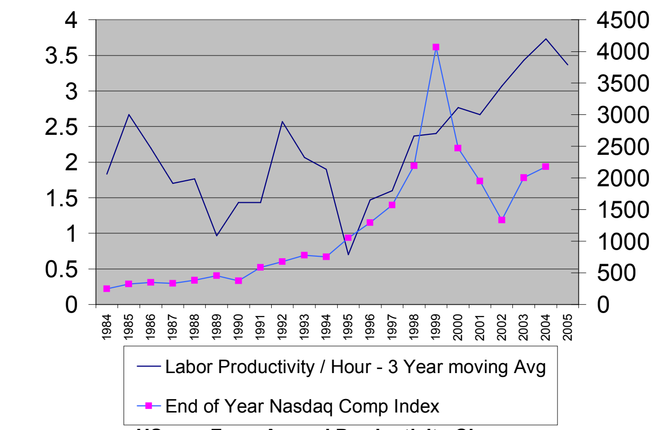
Table 3	
US Non Farm MFP 1988-2004	
Average Annual Change (%)	
1988 - 1994	0.63
1995 - 2000	0.98
2001 - 2004	1.90

Source: U.S. Department of Labor, Bureau of Labor Statistics

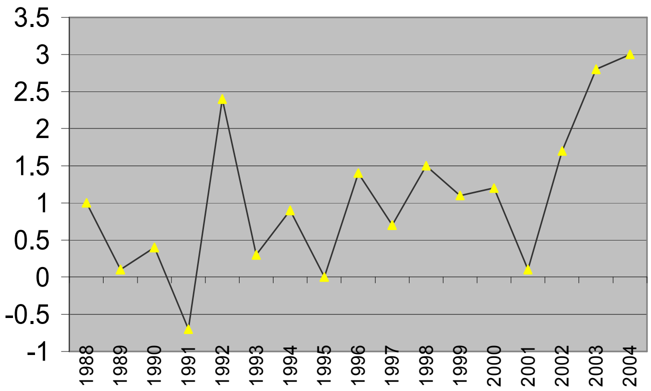
Evaluating trends and business cycle productivity data provides further support to our observation. Figure 3 depicts moving average, year over year, non farm labor productivity change from 1951 to 2005. From this figure it is clear to see that the current productivity change pattern clearly differs from previous cycles. Trend line slopes indicate a change in trend direction in the mid 1980, acceleration in the mid 1990s and further accelerated significant after 2001.



US non Farm Labor Productivity / Hour
Annual Change (%)
Figure 3



US non Farm Annual Productivity Change
Annual Growth (%)
and the Nasdaq Stock market Index
Figure 4



US Non Farm Multi Factor Productivity
Annual Change (%)
Figure 5

Figure 4 presents a rolling 3 year average of non farm annual productivity change together with the end of year Nasdaq stock market index. One can immediately notice the change in the cyclical productivity pattern which shows a striking out of pattern increase at about the same time that the Nasdaq bubble is coming to an end. Figure 5 plots year over year annual MFP change for the Non Farm sector. The unprecedented growth sequence following 2002 represents an unprecedented increase in MFP acceleration with three consecutive data point more than double the value of long term averages.

The significant productivity increase following the deflation of the valuation bubble is consistent with the notion that the bubble builds up prior to the massive adoption of the new technology as is indicated by our model. Once pervasive utilization of the new technology is common, productivity figures rise while at the same time some of the uncertainty associated with the innovation is reduced thus deflating the valuation of new technology firms even though productivity is improving.

III. Related Literature

Blanchard (1979) was first to point out that self ending speculative bubbles are consistent with rational expectations, he also pointed out that models may be built incorporating the effect of speculative bubbles on the real economy. Classic Macro bubble theory, starting with Tirole (1985) has focused on the viability of permanent bubbles and their impact on welfare and growth in general equilibrium. Initial macro research was focused on bubbles associated with non productive assets and concluded that in an endogenous growth setup these bubbles are always harmful to growth and welfare. Olivier (2000) was first to focus on bubbles associated with productive assets and showed that such perpetual valuation bubbles may encourage entrepreneurship, firm creation, investment and growth.

Following the massive internet and communication bubble, research of transitory bubbles has received renewed attention. Numerous papers suggested mechanism which may provide an explanation to the creation and destruction of such bubbles. Asymmetric information or beliefs provide a rich set of possible drivers (see

Brunnermeier (2001) for an extensive overview) others proposed behavioral and herding explanations with possible departures from rationality (see Shiller (2000)).

The model presented in this paper assumes symmetric information with uncertainty. As first described by Sampson (2002), uncertainty associated with a future technology change may create a rational bubble like effect in firm value. Pastor & Veronesi (2002) created a framework linking stock market valuations to firm age and uncertainty about average profitability. In their work the possible impact of profit volatility on the Market to Book ratio is substantiated. The volatility of profitability is shown to have a positive effect on the M/B ratio. In later work Pastor & veronesi (2006) apply this framework to the peak of the 2000 Nasdaq bubble and show that the level of uncertainty required to generate the observed extreme valuations is high but plausible. In these types of models asset value depreciation does not imply that ex-ante mean expectations were on the average over-optimistic, rather, depreciation may be a result of a reduction in uncertainty.

Valuations, per-se, are not a strong driver of long term real change if they do not influence real activity. Morck, Shleifer and Vishney (1990) were among the first to methodically test the answer to the questions: “Is the stock market a side show?” . Do stock market valuations significantly impact long term investments and financing decisions? While their answer was somewhat inconclusive, recent work by Baker, Stein and Wurgler (2003) demonstrate the significant impact of stock market movements on corporate investments by equity constraint firms. Polk & Sapienza (2004) show that stock market mispricing may effect corporate investment decisions even after controlling for the equity effect. They empirically show that this impact is stronger for firms with higher R&D intensity. Gilchrist, Himmelberg and Huberman (2004) develop a model which ties dispersion of beliefs with an increase in valuations which in turn influence firms’ equity issuance and real investment.

In a very recent paper published on the NBER, after our work was first presented, Pastor and Veronosi (December 2005) link uncertainty associated with adoption of a new innovation to a stock market bubble like behavior. Both models share the basic association of uncertain technology change, adoption and valuation however the Pastor & Veronesi paper relates to a centralized homogeneous economy with an experimentation process and a centralized decision point. The focus of their paper is a binary economy wide adoption decision, which in turn creates a valuation reversal upon realization that full adoption by the economy is inevitable. Most modern innovations develop in an environment of decentralized decision making, with uncertainty and market factors contributing to the decisions of independent value maximizing economic agents. Our decentralized model, presented in this paper, focuses on the varying degrees of adoption as well as on the feedback mechanism between uncertain technology adoption, network externalities and long term productivity

Jermann and Quadrini (2003) provide a causal explanation linking the 1990s stock market boom with productivity gains during the bubble. Although the mechanics and time focus of their paper and ours are very different we share an important feature, expectations about a future change in productivity or growth serve as a driver to increased present firm valuations which in turn impact production, productivity and growth. Their model emphasizes current production associated with firm size distribution. This distribution is affected by the bubble as financial constraints for smaller firms are relaxed during the bubble. However, Jermann and Quadrini focus on the boom part of the cycle, the productivity impact in their paper lasts as long as the bubble does. Our analysis, as well as updated data, show that that the significant productivity impact occurs not during, but rather after the deflation of the valuation bubble.

Studies by Oliner and Sichel (2000) and others attributed a significant portion of 1995-2000 productivity gains to the increased investments in, as well as increased productivity of, the ICT sector. These studies were published prior to the 2001-2004 data which showed continued productivity gains coinciding with a sharp decrease in ICT investments. Armed with more recent data it is more difficult to utilize their explanation to the overall productivity change profile. Gordon (2004) attempted to apply his 1979 "end of expansion" mechanism to the turn of the century productivity data and concludes that such cyclical mechanisms can not explain the data. Gordon suggests another mechanism which he calls the early recovery bubble (this time referring to a bubble in productivity measurements) which may explain the 2002-2003 data which were available when his paper was introduced. If this theory was correct we should have observed a sharp decline in 2004-2005 productivity data, contrary to recent reports.

Yang and Brynjolfsonn (2001) focused on intangible capital which exists on the input as well as the output side of productivity measurements. Their arguments, applied to the 1995-2000 period, would suggest unmeasured output exceeding unmeasured input thus according to this explanation real productivity gains during this period were actually much higher than reported. Applying their theory, Gordon (2004) suggests that part of the increased productivity in the 2001-2003 period may be due to these non tangible outputs, produced prior to 2000 and utilized but not counted during subsequent years. Gordon adds an additional explanation, pointing out to the savage cost cutting and associated organizational changes which followed the post bubble period. Both of these explanations are of a transitory nature. Yang and Brynjolsonn's argument relies on changes in the direction and velocity of ICT investments , which occurred in 2000/2001 while Gordon's cost cutting argument should only impacts the periods immediately following the reorganization.

Gordon's updated cyclical effects, as well as the non tangible theory of Yang and Brynjolsonn all suggest that 2003 Productivity change should have been the "high water mark", as Gordon himself wrote. Updated productivity figures, after 2003, show continued productivity improvement, well beyond the scope of changing investment velocities or one time structural changes which occurred earlier. We propose a more direct explanation for increased productivity growth following the bursting of the bubble: Adoption and implementation of a superior technology augmented by network externalities and propelled by the bubble itself. In our model the expectations for such a spectacular performance together with the associated uncertainty of such a revolutionary technology were the cause of the stock market bubble. When the technology was widely adopted the stock market collapsed. The stock market bubble burst not because the technology did not live to its expectations, it indeed performs as is evidenced by the productivity data, but because much of the uncertainty regarding the new technology was resolved. We argue that in such a setup the feedback between expectations, uncertainty and market value on one side and technology adoption and investments on the other, may produce a bigger bang when the technology at hand is associated with network externalities. The ability of expectations to create a bubble and impact market outcome in macro growth literature was also modeled by Nyssen (1994) who pointed out that a permanent but weak, non rational, optimism can create a sustainable bubble in a Grossman & Helpman endogenous growth model and that the resulting equilibrium may exhibit increased growth and welfare.

From a methodology view our model introduces uncertain innovation and heterogeneous firms into a Lucas (1978) type economy. Greenwood and Jovanovic (1999) also apply future technology change into a Lucas economy, their model assumes certainty and no decision making by the firms. In our model heterogeneous, value maximizing, firms face uncertainty regarding the expected growth benefits of a future innovation and decide if and when to adopt it. Our framework pays special attention to the co-interaction and long term productivity impact of uncertain technology adoption and network externalities in a dynamic setting.

IV. The Model

Our model is an extension of a Lucas (1978) style economy with the introduction of heterogynous firms and uncertain technology change. At the outset firms utilize an existing technology with a known growth rate. At some point in time information regarding a new technology is revealed. This new technology may be utilized, in the future, by existing firms. Firms are heterogeneous with respect to the gains from this new technology and optimally decide if they wish to adopt the new technology or continue production with the old one. We may interpret the Lucas trees as independent firms or alternatively as sectors with heterogeneous benefit from the new technology. We incorporate in the model the possible existence of externalities, which ties in potential productivity gains with the number of firms adopting the new technology.

As we shall detail in the following sections, bubble like valuation profiles, induced by uncertainty, impact technology adoption. In a setting with strong externalities this bubbly path may propel the market to an equilibrium with a higher long term growth. In some settings the bubble may correct a possible market failure which occurs as firms fail to fully internalize externalities. Alternatively, in a setup with multiple-equilibrium we may perceive the bubble as assisting the market in directing a large enough mass of economic agents to the higher growth equilibrium. The bubble may be also be seen as a mechanism which induces firms to privately undertake certain risks which may propel the economy to a higher equilibrium, risks which they would alternatively have avoided.

At the outset all trees in the economy utilize a known technology with production / dividend growing at an expected per period growth g^0, with $g^0 \sim N(\mu_{g^0}, \sigma^2_{g^0})$. Period t dividends are depicted as D(t) and consumption as C(t). The expectation for the next period dividend is $E_t[D(t+1)] = D(t)E_t[e^{g^0}]$. The instantaneous utility from consumption is given by utility function U. δ is the subjective inter-temporal discount factor.

Agents optimize their targets in continuous time with a finite horizon *T*. The equilibrium value of a tree in this initial state is thus the present value of all future dividends as summarized in equation (1). [†]

$$(1) \quad P(t) = D(t)\int_0^T e^{(g-\delta)\tau} E_t\left[\left(\frac{U'(C(t+\tau))}{U'(C(t))}\right) \right] d\tau$$

$$\text{Where } \; g = \mu_{g^0} + \frac{\sigma^2_{g^0}}{2} \qquad \ddagger$$

[†] One may regard the finite horizon as a decade long approximation of hyperbolic time discounting. Hyperbolic discounting has been found to provide a better explanation for empirical evidence regarding savings and consumption. See Harris & Laibson (2001).

[‡] Jensen's Inequality shows that $g > \mu_{g^0}$, the explicit definition of g above is derived directly from the LogNormal Properties.

Introduction of New Technology

At a certain time a new innovation is introduced. This new technology may only be utilized at a future date t_1. After such date the average per period growth rate for firms utilizing the new technology is expected to be g^1 with said new growth rate defined as an improvement g^c over current technology. This innovation is expected to support enhanced growth for t_c periods following t_1.

$$g^1 = g^0 + g^c$$

The value of g^c is not known with certainty. Initial information regarding the new technology is incorporated in the expectation that this new technology growth rate will be drawn from the normal distribution: $N(\mu_{g^c}, \sigma^2_{g^c})$. The mean and variance of the source distribution may evolve based on the experience of innovation implementing firms.

Two separate growth uncertainties exist in the market, the first uncertainty is the idiosyncratic uncertainty relating to per period / firm realization, while the second pertains to the unknown growth impact of the new innovation. The realization uncertainty variance is $\sigma^2_{g^0}$ while the variance of the source distribution of the future innovation growth is $\sigma^2_{g^c}$.

The expected τ period future growth is defined by equation (2):

$$(2)\quad E\left[e^{g^{1,1}} e^{g^{1,2}} \ldots\ e^{g^{1,\tau}}\right] = e^{\tau(\mu_{g^0} + \mu_{g^c}) + \tau\frac{\sigma^2_{g^0}}{2} + \tau^2\frac{\sigma^2_{g^c}}{2})}$$

Where $g^{1,j}$ is the innovative period j growth factor.

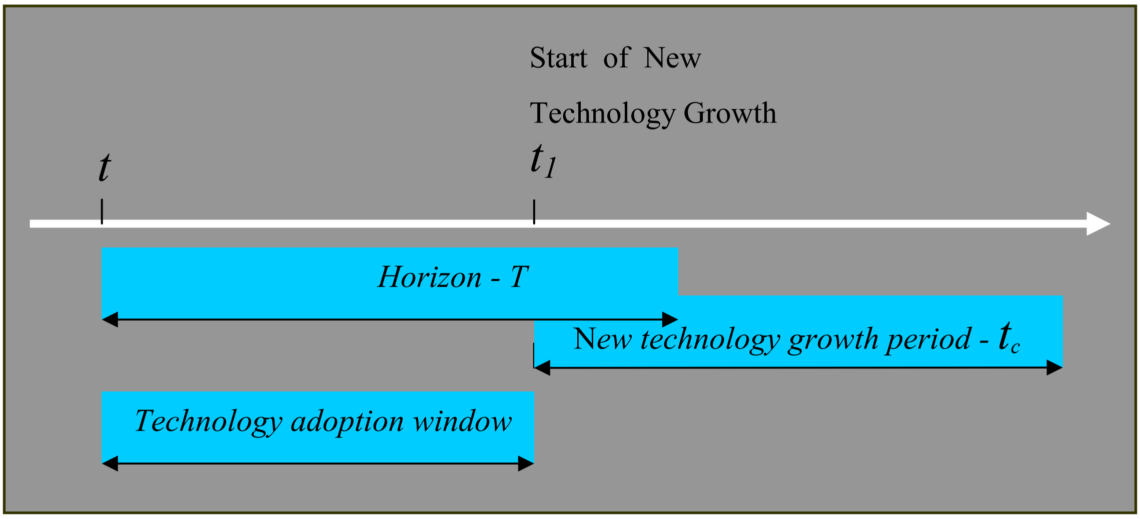
Using the Lognormal properties we know that long term average growth is influenced not only by the mean of the associated Normal distribution but also by its variance. Both variance values impact long term mean growth differently. Each realization shock is idiosyncratic, thus long term impact of $\sigma^2_{g^0}$ on τ period growth is factored by t. The same, yet unknown, new technology growth premium impacts all future periods, thus the impact of $\sigma^2_{g^c}$ on τ period growth is factored by t^2.

Heterogeneous firms & technology adoption prior to t_I

The new technology is not applicable to all firms in the same way. The actual expected growth for specific firm i utilizing the new technology is $g_i = g^1 - \theta_i$. Where $\theta_i \in [0,1]$ is a specific technology suitability parameter, distributed according to a distribution function with a CDF F.
The new technology is applicable to a portion of the firms, the size of this potential new technology sector shall be $s \in [0,1]$, were a value of 1 means that all firms belong to the potential new technology sector.

We may interpret this technology applicability value as a firm specific technology utilization cost which should be undertaken by each firm in order to utilize the new technology and enjoy its associated benefits. Alternatively this parameter may simply define the suitability of the new technology to the specific sector or firm. Each firm knows its specific utilization value with certainty and may be required to invest a marginal sum to credibly announce this value.

Figure 6 outlines the basic time-line of the model. Firms must decide if they wish to adopt the new technology prior to t_I. In our basic setup we assume the technology decision is binding following t_I. Prior to t_I-T the new technology does not effect firm valuation thus all firms continue to utilize the old technology and have no reason to contemplate adoption. During the period [t_I-T,t_I] firms decide if they wish to adopt the new technology or maintain operations using the old technology.



Basic Time Line

Figure 6

We assume firms independently act as market value maximizers and announce the adoption of the new technology as soon as conditions are such that firm value will increase following such announcement. There are no agency issues in our model since ownership of each firm is equally distributed among all identical consumers.

$P_i^1(t)$ is the period t value of an innovation adopting firm i, with suitability parameter θ_i [§]

$$(3)\quad \frac{P_i^1(t)}{D(t)} = E_t\left[\int_0^{t_1-t} \rho(t,\tau)\ e^{g^0\tau} d\tau\right] + E_t\left[\int_{t_1-t}^{\bar{T}} \rho(t,\tau)\ e^{g^0(t_1-t)} e^{g_i(t+\tau-t_1)} d\tau\right]$$

$$+ E_t\left[\int_{\bar{T}}^{T} \rho(t,\tau)\ e^{g^0(t_1-t)} e^{g_i t_c} e^{g\ (t+\tau-t_1-t_c)} d\tau\right]$$

Where $\rho(t,\tau) = e^{-\delta\tau}\dfrac{U'(C(t+\tau))}{U'(C(t))}$ is the inter-temporal utility adjusted discount factor,

and $\bar{T} = Max\{T, t_1 + t_c - t\}$, $g_i = g^1 - \theta = g^0 + g^c - \theta_i$

[§] The new technology is expected to produce enhanced growth only following t_1, thus production for periods prior to t_1 are not dependant on the technology decision. If the time horizon T is greater than t_c then the third section of the price definition is Null.

Firms are atomic and do not individually impact the production or consumption of the whole economy, each one takes the known adoption rate as given. We assume information regarding the adoption rate is distributed to all players which internalize market adoption within a time period Δ. We shall return to the information delay later in this paper when we describe the dynamic impact of network externalities. When evaluating the benefit of new technology adoption each individual firm evaluates equation (1) and (3) utilizing the same expected values for future consumption thus the discount factors for both equations are equal.

Equation (4) details the explicit impact of the adoption decision on the market value of firm *i* under the case of $T \leq t_c$. Equation (5) summarizes the adoption decision variable calculated by each firm at time *t*. When $V_i(t) > 0$, firm *i* announces the adoption of the new technology.

$$(4) \qquad E_t\left[\int_{t1-t}^{T} \rho(t,\tau)\ D(t)e^{g^0(t1-t)}e^{g_i(t+\tau-t1)}d\tau\right] - E_t\left[\int_{t1-t}^{T} \rho(t,\tau)\ D(t)e^{g^0\tau}d\tau\right]$$

$$(5) \qquad V_i(t) = E_t\left[e^{g^0(t_1-t)}\int_0^{T-(t1-t)} e^{-\delta\tau}U'(C(t_1+\tau))(e^{g_i\tau} - e^{g^0\tau})d\tau\right]$$

As firms are atomic, the private old technology growth realization for a firm is not correlated with future consumption; however the new technology added growth component by definition correlates future economy consumption with the growth results of a specific new technology firm. This covariance varies over time and is impacted by the adoption rate. The covariance increases with the number of adopting firms as well as with *τ*.

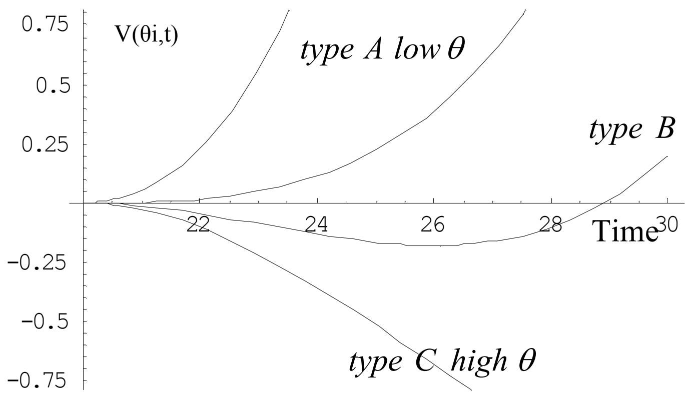
Each firm is faced witch a decision whether to remain with a known growth path which is not correlated with the realization of the new technology or to adopt the new uncertain innovation, possibly enjoying increased growth, but at the same time \correlating its growth rate with the yet unknown market wide realization of the new technology. The adoption decision is thus impacted not only by the innovation parameters but also by the economy wide adoption rate.

Let us first evaluate the path of V under the special case of risk neutrality. We can focus on the differential growth section, as described in equation (6).

$$(6)\ E_t\left[e^{g_i\tau} - e^{g^0\tau}\right] = e^{g\tau} E_t[e^{(g^1-\theta_i)\tau} - 1] = e^{g\tau}(e^{(\mu_{g^c} + \frac{\sigma^2_{g^c}}{2}\tau - \theta_i)\tau} - 1)$$

If $\mu_{g^c} > \theta_i$ then firm i adopts the innovation as soon as it is within view (at t_{1-T}), while on the other hand if $\mu_{g^c} + \frac{\sigma^2_{g^c}}{2}T < \theta_i$ then firm i will never decide to adopt the technology prior to t_1. In the span between these two extremes there may be a cross-over point such that for every τ greater than the cross-over point the new technology yields a superior mean value for that portion of the future.

Figure 7 illustrates an example of the value function calculated for firms with different firm specific suitability parameters under risk neutrality.**



The value of new technology adoption for different firms under risk neutrality

Figure 7

We can view three types of firms; firms of type A, have a low enough θ, thus they adopt immediately and their value function is monotonically increasing as we move closer to technology implementation. Type B firms initially have negative adoption value which may become positive as we move closer to technology adoption. Such

** Adoption value calculated under the assumption that the firm takes the number of adopting firms, n, as given with an information delay of 1 period..

firms will not initially adopt the technology at introduction but may eventually announce adoption prior to technology implementation as their decision variable value turns positive. In the specific parameters used to generate the above graph t_1=30 thus the depicted B type firm adopts the technology 2 periods prior to the new technology market utilization. Type C firms will never adopt the technology and their decision variable is monotonically decreasing as we move forward in time.

The degree of risk aversion, as well as the adoption rate and potential sector size impact the covariance between private technology gains and consumption, which in turn impacts future expected marginal utility thus impacting *V*. As we move closer to t_1 the new technology variance increases the future expected mean production. At the same time the variance of future production increases as well as the covariance between the private expected production and future consumption, thus increasing the impact of the future consumption based discounting on the current value of the future production stream.

Let us now evaluate various conditions which may provide for a monotonically increasing adoption profile as we move closer to t_1. Without loss of generality we assume $\mu_{g^0} + \frac{\sigma^2_{g^0}}{2} = 0$, i.e. the effective old technology economy growth rate is 0. For brevity we shall omit the g^c subscript from the new technology growth variance. Thus σ^2 shall stand in for $\sigma^2_{g^c}$.

Lemma 1

If the potential new technology sector s is sufficiently small[††] then for any θ and t_0 such that $V(\theta,t_0)>0$, $V(\theta,t)$ is monotonically increasing in *t* for $t \in [t_0, t_1]$.

This result is derived from the fact that asymptotically a small enough new technology sector will result in a marginally constant consumption based discount factor, and as long as our economy deals with normal goods the result is immediate.

[††] Given U and the distribution of g , a sufficient condition for lemma 1 is :
$$E\left[e^{\kappa g} U'(se^{\kappa g} + 1 - s)\right] \geq E\left[U'(se^{\kappa g} + 1 - s)\right] \text{ for } g = \tilde{g}, \tilde{g} \sim N[\mu_g, \sigma^2],\ \mu_g > 0,\ 0 < \kappa \leq T$$

In order to categorize adoption behavior for new technology sectors which have a more significant impact on economy wide production & consumption we shall define the following utility attribute:

Let us call a utility function which satisfies the constraint outlined in equation (7) a "growth supporting risk averse utility" of degree τ - *GSU(τ)* ‡‡

$$(7) \qquad E\left[e^{\kappa g}U'(e^{\kappa g})\right] \geq E\left[U'(e^{\kappa g})\right] \qquad §§$$
$$g = \tilde{g}_{,}\ \tilde{g} \sim N[\mu_g, \sigma^2],\ \ \mu_g > 0,\ \ \kappa \in [0, \tau]$$

If a utility function is *GSU(τ)* for **any** τ and **any** σ we shall call it an SGS utility.

$U(x) = \sqrt{x}$ and $U(x) = \frac{x^{1-\alpha}}{1-\alpha}$ $\quad for\ \ 0 < \alpha < 0.5$ are examples of risk averse utility functions which have the SGS property while $U(x) = \ln(x)$ is not SGS. ***

Lemma 2

If the utility function is of type *GSU*(t_c) then for any θ and t_0 such that V(θ, t_0)>0 , V(θ, t) is monotonically increasing in *t* for $t \in [t_0, t_1]$.

If the utility function satisfies *GSU*(t_c) then as we move closer to t_1 the impact of the increasing future mean production dominates the impact of the utility based discounting factor. As we move closer to t_1 firms which have a marginal benefit from adopting the new technology compare the overall value of an almost certain production value which has no correlation to the potential variance in future consumption to a higher mean production value which is increasingly more correlated with future consumption. The *GSU* definition is sufficient to guarantee the monotone profule as it infers to the decision value of a marginal firm under the assumption that

‡‡ Complete notation should specify $GSU(\tau, \mu_g, \sigma)$, for brevity we use *GSU(τ),* subject to a known source distribution for g.

§§ For the classic CRRA utility function $\frac{x^{1-\alpha}}{1-\alpha}$ this condition reduces to $\mu_g > (\alpha - 0.5)\tau\sigma^2$

*** Recent estimates for relative risk aversion obtained experimentally produce measures of rra in the range of 0.3 to 1; Nielsen (2001) , Barr (2003), Cardenas & Carpenter (2005) obtain measures between 0.32 and 0.81 using a choice of lotteries. Holt & Laury (2002) obtain results between 0.68 and 0.97 in accept reject lotteries which often produce slightly higher measures of risk aversion.

future consumption is fully correlated with the technology outcome as all other firms have adopted the technology. The degree of (*tc*) guarantees that this effect shall continue until t_1.

Let us define $\hat{\theta}_t$ as the value which solves $V(\hat{\theta}_t, t) = 0$.

Lemma 3

If *s* is sufficiently small, in the sense of *Lemma 1*, or the utility function is *GSU*(t_c) and there exists t_0 such that $\hat{\theta}_{t_0} > 0$, then for any $t \in [t_0, t_1]$:

- $\hat{\theta}_t$ is unique
- All firms with $\theta_i < \hat{\theta}_t$ adopt the new technology no later than time *t*.

This *Lemma* is a result of the monotone implications of *Lemma* 1 & 2 and the definition of the value function. The mean growth rate for a firm with $\theta_i < \hat{\theta}_t$ is higher than a firm of type $\hat{\theta}_t$ and the same variance and discount factors are used when calculating the decision parameter.

If the conditions of *Lemma 1* or *Lemma 2* are satisfied we may conclude that the adoption decision by an individual firm is naturally binding until t_1, as the adoption value parameter is monotonically increasing for an adopting firm until t_1.

From *Lemmas* 1 , 2 & 3 we can directly derive the following proposition:

Proposition 1

If the potential new technology sector is sufficiently small, in the sense of *Lemma 1*, OR if the utility function is *GSU*(t_c) then :

- The number of firms adopting the technology will increase monotonically as we approach t_1.
- If adoption occurs (i.e. $\hat{\theta}_{t_0} > 0$ or some t_0) then the adoption indifference value shall strictly increase monotonically over [t_0, t_1]

Proposition 1 holds for any shape of *F*(.) as well as any time horizon *T*. As we move closer to t_1 more firms adopt the technology, even though no new technology information is available. The actual number of firms which adopt the new technology at any given time t is $F(\hat{\theta}_t)$. [†††]

It is important to emphasize that for every utility function that is not $GSU(t_c)$ there is a robust support over (σ, γ, s) which nevertheless produces a monotonously increasing adoption profile. This is due to the fact that the *GSU* characteristic assumes full correlation between the economy and the new technology growth, while in our model, as in reality, only a potion of the firms adopt the given technology thus the utility based discount factor is only partially impacted even for very risk averse functions.

The velocity of adoption is obviously impacted by the utility characteristics as well as the size and distribution of the actual adopting sector. If the actual adoption rate is small enough we can expect $\hat{\theta}_t$ to increase asymptotically linearly as there is no significant impact of the future marginal utility profile, however in the general case, when no externalities are involved, $\hat{\theta}_t$ will increase at a decreasing rate due to the production impact on the consumption based discount factor.

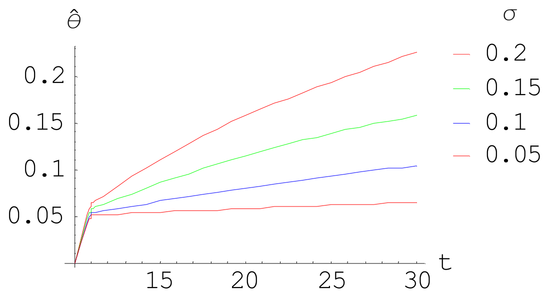
Proposition 1.5

If the utility function is SGS then: $\frac{\partial \hat{\theta}_t}{\partial \sigma} > 0$ and $\frac{\partial \hat{\theta}_t}{\partial t \partial \sigma} > 0$.

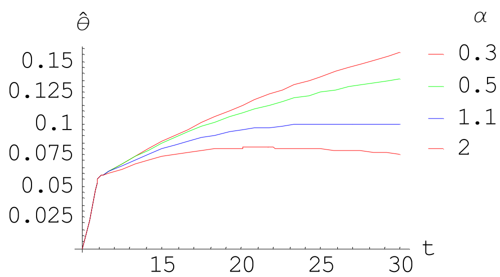
If the utility function is SGS then the rate and volume of firm entry are always positively correlated with the degree of uncertainty associated with new technology growth.

[†††] A monotonic adoption profile may be the outcome in our model even if the conditions of Proposition 1 do not hold, depending on specific parameter values. The specified conditions of Proposition 1 are sufficient but not necessary to generate this result.

If the utility function is SGS then by definition equation (7) holds for any σ. From the lognormal properties a higher growth variance results in a higher mean future production for any τ. Both of these results together generate *Proposition 1.5*.



Adoption indifference profiles under varying levels of new technology uncertainty (σ),
With an SGS utility function CRRA (α) = 0.3
Figure 7a



Adoption indifference profiles under varying levels of risk aversion (α) with σ fixed at 0.15
Figure 7b

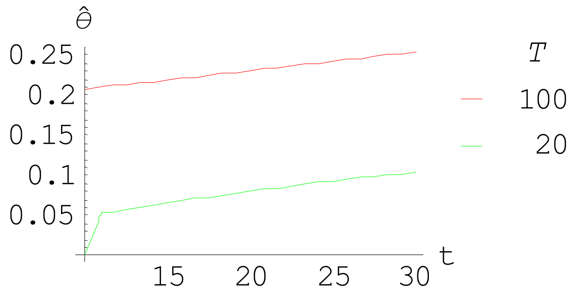
$$T = 20 \quad t_1 = 30 \quad t_c = 20 \quad \mu_{g^c} = 0.05, \; U(c) = \frac{c^{1-\alpha}}{1-\alpha}, s = 1$$

Adoption Indifference Profiles approaching t1
Figure 7

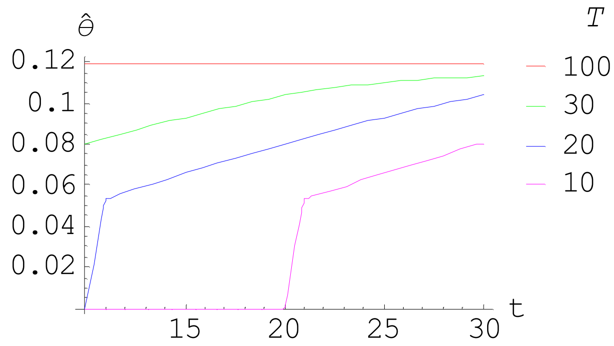
Figure 7 details simulated examples of the adoption indifference profiles under varying degrees of uncertainty and risk aversion. Figure 7a shows that under an SGS utility, higher uncertainty increases the slope of the adoption indifference profile, while figure 7b exemplifies impact of increased risk aversion on the adoption profile.

The optimization horizon T impacts both the level of technology adoption and its pace. For a an SGS utility function the technology adoption indifference profile will remain monotonously increasing regardless of the value of T but the relative rate of change will decrease as T increases. Figure 8 depicts the simulated adoption indifference profile under different horizons. Figure 8a simulates the profile under the assumption that the maximum term of new technology impact is equal to the horizon.

Figure 8b assumes new technology impact is constant at 20 periods regardless of the horizon.



Adoption indifference profiles under varying horizon (*T*),
With an SGS utility function, assuming $T = t_c$,
Figure 8a



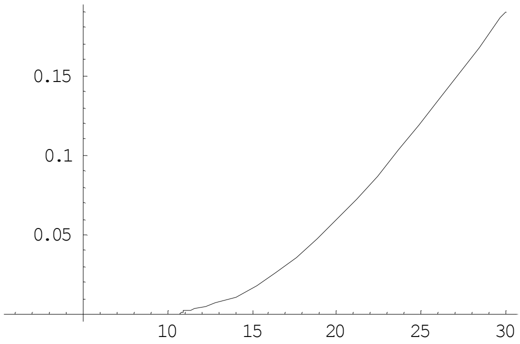
Adoption indifference profiles under varying horizon (*T*),
With an SGS utility function and a fixed new technology impact period ($t_1 = 30, t_c = 20$),
Figure 8b

$\mu_{g^c} = 0.05,\ \sigma = 0.1,\ U(c) = \frac{c^{1-\alpha}}{1-\alpha},\alpha = 0.3,\ s = 1$

Adoption Indifference Profiles approaching t1
Figure 8

The actual number of firms announcing technology adoption depends on the specific distribution of θ. A uni-modal distribution for θ, were $\hat{\theta}_t < Mode[\theta]$ for some $t<t_1$ will most probably generate an adoption rate which at least for a period of time prior to t_1 increases at an increasing rate.

Figure 9 displays an illustrative simulated adoption pattern as the market approaches technology implementation. The figure depicts adoption rate simulated results for θ ~ Beta Distribution(6,20), with other parameters as in Figure 7 with α = 0.3 and σ = 0.15.



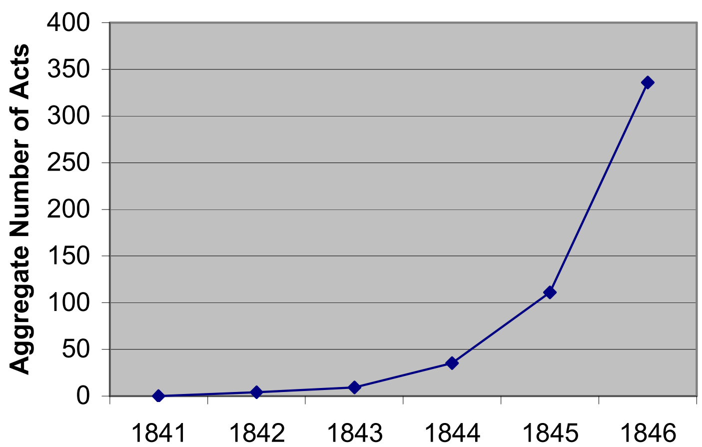
Example of model implied adoption level approaching t_1

$T = 20 \;\; t_1 = 30 \;\; t_c = 20, \;\; \mu_{g^c} = 0.05, \;\; \sigma = 0.15, \;\; U(c) = \frac{c^{1-\alpha}}{1-\alpha}, \;\; \alpha = 0.3, s = 1$

θ ~ Beta Distribution (6,20),

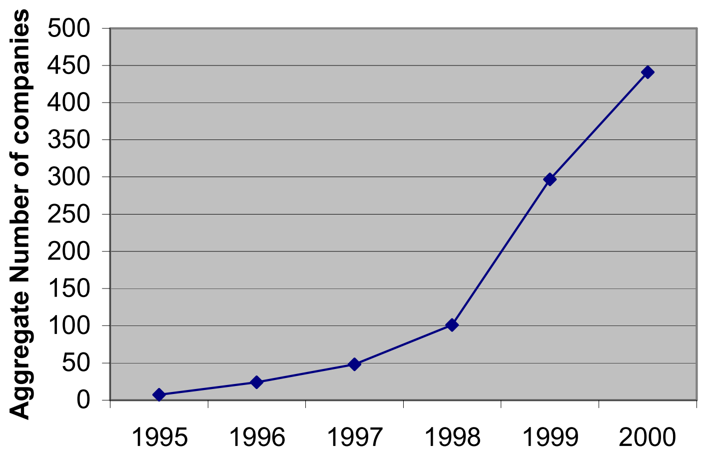
Figure 9

Figures 10 and 11 display actual adoption rates associated with the internet and railway bubbles respectively. Figure 10 shows the aggregate number of authorized acts to establish railway companies during the Railway bubble of the 1840s. Figure 11 displays the number of initial venture backed financing events for Consumer targeted internet companies (Hendershott (2004)). These .com companies represent the segment which represented the most significant paradigm shift during the internet bubble expansion. We may regard these figures as a stylized indication to the trajectory and rate of internet technology adoption by firms during this period.



Authorized acts to establish new rail lines

Figure 10



Initial venture backed financing of consumer targeted .Com Companies
Figure 10

Network Externalities

Let us define n_t as the fraction of the applicable new technology sector firms which have adopted the new technology at time *t*. $n_t = F(\hat{\theta}_t)$. In the spirit of GPT literature (Bresnahan and Trajtenberg (1995) and others) as well as network externality models (Katz and Shapiro (1985) and many others) we assume that at least for a sub-range of n there exists a positive externality between the share of technology adoption and expected benefits from the new technology. See Oz Shy (2001) for an overview of the specific economic aspects associated with network industries. While we maintain the non explicit nature of this model we refer the reader to Zvilichovsky (2004) for additional examples of possible micro structures supporting such positive externalities.

In the presence of externalities the new expected average growth rate shall take into account the evolution of n with a mean new technology growth rate $\mu_{g^c}(n)$ where $\frac{d\mu_{g^c}}{dn} \geq 0$ for $n \in [0, \hat{n}]$ $, \hat{n} < 1$.

We regard the adopting sectors as contributing to increased productivity by both direct network effects (such as those described in the phone, fax or other similar industries) as well as complementary effects, where a few components manufactured by different sectors, utilizing compatible technology, are required to enjoy the full benefits of a complete system.

We assume that firms are aware of the network effect function $\mu_{g^c}(n)$ and know the rate of adoption with a time delay of Δ. When making their adoption decision firms take $n = n_{t-\Delta}$ as given. Knowledge of the adoption rate enters the adoption criteria with two effects; The first, which has a negative impact on adoption, affects the consumption based discount factor which incorporates future consumption and its related uncertainty. The second effect is the externality effect which at least for a portion of the applicable adoption range has a positive effect on valuation and adoption of new technology.

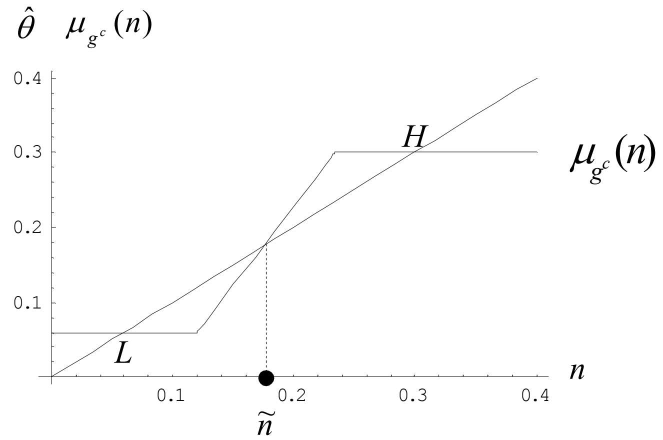
A positive feedback mechanism incorporating technology uncertainty, adoption and the impact of network externalities may play an important role in propelling both adoption and valuations with an increased velocity. Under the conditions specified previously, uncertainty increases firm valuations which encourages technology adoption as we move closer to t_1. At the same time the increased adoption may increase, via network externalities, the expected new technology productivity which may in turn further increase market valuation which further increases adoption.[‡‡‡]

The interaction between the uncertainty induced adoption profile and the externality function may be easily explained by the following simplified example depicted in Figure 12. For simplicity of exposition we assume that the new technology exhibits a piece-wise linear externality function, and $s=1$,. This externality function is a simplified approximation of a typical S shaped externality curve often used in the literature. The horizontal axes is the adoption rate, while the vertical axes exhibits $\mu_{g^c}(n)$, the new technology growth rate parameter. Under our simplifying

[‡‡‡] In the case were externalities increase the variance of the new technology growth, under SGS utility characteristics, we should expect further amplification of both valuations and adoption.

assumptions with a Uniform θ distribution under full certainty we get $n_t = \hat{\theta}_t$ and $\hat{\theta}_{t+\Delta} = \mu_{g^c}(n_t) = \mu_{g^c}(\hat{\theta}_t)$. Assuming free entry and exit as well as enough information cycles to allow convergence there are three possible equilibria, of which one is non stable.

In the specific example depicted in the graph we used $\mu_{g^0} = 0, \mu_{g^c} = 0.06$, thus under all time certainty and atomic firms only those with suitability parameter $\theta_i < 0.06$ will adopt the technology and the economy will stay at the Low Equilibrium. If under some process the uncertainty induced adoption rate results in an adoption rate which is higher than adoption rate $\tilde{n}$ and assuming that following the resolution of uncertainty such adoption rate does not drop below $\tilde{n}$ then the long term equilibrium under these simplified assumptions would be at point H which exhibits both a higher adoption rate and a higher technology impact.



Interaction between a naïve adoption rate and a Piece-Wise Linear externality Function

Figure 12

Assuming a fixed variance with an externality driven mean productivity increase actually generates a relative decrease in the impact of uncertainty. Under certain market structures it is plausible to assume that the variance of future growth is also directly impacted by n_t. If we were to assume underlying micro structures with uncertainty and heterogeneous beliefs the number of adopting firms may increase the entropy of the game thus leading to an increase in the variance of new technology growth. This possible increase in uncertainty may further impact valuations, adoption and post bubble productivity. We believe that direct externality impact on the uncertainty of future growth is an interesting topic for further research, however all simulations in our model were performed assuming no externality impact on the variance of the potential new technology growth.

Information update following new technology experience

Following t_1 all firms which have adopted the new innovation begin to utilize it in production. Information is collected regarding the realized growth parameters of the innovating firms. Growth information parameters are updated based on these observed realizations.

We assume that at given intervals firms, credibly publicize their production and growth information. This new information allows the economy to update the estimates for the mean and variance of the distribution which summarize the information regarding the new technology growth. Through-out the remainder of this section we shall refer to σ and μ as the mean and variance of the new technology growth information omitting the g^c subscript. . The process can be Bayesian or may simply follow sampling theory estimations. Due to the central limit theory, in both methods an estimator can be constructed to converge to the true value of μ with the new technology variance parameter converging to 0 as the number of samples increases. The amount of new information gathered, following t_1, is proportional to the time elapsed after t_1 as well as to the number of firms which adopted the new technology.

Assuming firms announce their results every period, each period an additional n growth samples are added to the collective information set. At every period t, $t>t_1$, $n*(t-t_1)$ samples are available in the updated data set.

We regard the initial values attributed to μ and σ^2 as conjugate priors. To these priors the market assigns an information value which is equal to λ samples.

We shall now detail a sample procedure for updating information following t_1.

Let $\hat{\sigma}_{\tau}^{2}$ and $\hat{\mu}_{\tau}$ be the estimators computed for σ and μ from data collected up-to τ, $\tau > t_1$, these estimators are computed in the following method:

An average of all available per period growth values is continuously calculated. As the specific suitability parameters, for the innovating firms are publicly known, an estimator $\hat{g}^1$ for the value of g^1 can be calculated. According to the central limit theory this value converges to the actual value of $E(g^0 + g^1) = \mu_{g^0} + E(g^1)$. As μ_{g^0} is known we can thus obtain the estimator $\hat{\mu}$ for μ .

An intermediate standard S^2 estimator $\hat{\sigma}_{g^1}^2$ is calculated for the new technology per period growth. This estimator is expected to converge to the known $\sigma_{g^0}^2$ at a rate proportional to n*(t-t_1). Thus calculating $\hat{\sigma}_{\tau}^2 = \hat{\sigma}_{\tilde{\mu}}^2 - \sigma_{\tilde{\mu}}^2$ will produce the estimate for $\sigma_{g^c}^2$. As both g^0 and g^c are assumed to be normally distributed both of these estimators are not biased. $\hat{\mu}_{\tau}$ and $\hat{\sigma}_{\tau}$ converge to the actual value of μ_{g^c} and 0 respectively at a rate proportional to the number of available samples.

For ease of exposition we assume that that following t_1 no new firms join or depart from the technology network, and that the adopting firms provide a continuous flow of information regarding private growth realizations.

Following t_1, Participants update their current estimators for the new technology growth and variance based on their prior information combined with the timely updated $\hat{\sigma}_{\tau}^2$ and $\hat{\mu}_{\tau}$ estimators according to the following procedure:

For $\tau > t_1$

$$(8)\quad \mu_t = \frac{\lambda\mu_{t_1} + (\tau - t_1)n\hat{\mu}_{\tau}}{\lambda + (\tau - t_1)n}$$

$$(9)\quad \sigma_t^2 = \frac{\lambda\sigma_{t_1}^2 + (\tau - t_1)n\hat{\sigma}_{\tau}^2}{\lambda + (\tau - t_1)n}$$

As more realizations are announced μ_τ and σ_τ^2 converge to the true value of μ_{g^c} and 0 respectively.

V. Stock Market Valuations

In this section we describe the time path of stock market valuations. The stock market is expected to experience discontinuity when the new technology become operational and realization reduce the uncertainty associated with the new innovation. We evaluate the effect network externalities may have on market valuations. As an application of the model we also evaluate the success rate of adopting firms by adoption vintage and show that the model may provide an additional explanation to the sharp decline in success rates for late entrants.

Individual firm valuation

The value of a new technology firm with suitability value θ_i prior to t_1 is defined by equation (3) while its value following t_1 is:

$$(10)\quad P_i^1(t) = D(t)E_t\left[\int_0^T \rho(t,\tau)e^{g_i^1\tau}d\tau\right]$$

Subject to the following definition:

$$g_i^1 = g^1 - \theta_i$$

$$g^1 = g^0 + g^c$$

$$g^c is\ drwan\ from\ N(\mu_t, \sigma_t^2\ )$$

$$g^0 \sim N(\mu_{g^0}, \sigma_{g^0}^2)$$

Proposition 2

If the adoption profile is monotonously increasing[§§§] as we approach t_1 then:

a) The value of a new technology firm will increase monotonously up-to t_1, with $\frac{\partial P_i^1(t)}{\partial t \partial t} > 0$

b) Following t_1, a reduction in new technology uncertainty will depress the value of a new technology firm.

c) The probability of a price decrease following t_1 is monotonically increasing in $\Phi(\frac{\min(T, t_c) * \sigma}{2})$ where Φ is the CDF of the standard normal distribution[****]

.

Following t_1 all future T periods included in the valuation are impacted by the new technology. Realizations from new technology experience provide for a timely re-evaluation of the new technology parameters. As we have previously demonstrated, as more realizations are announced μ_τ and σ_τ^2 converge to the true value of μ_{g^c} and 0 respectively. Under a monotonously increasing adoption rate up-to t_1 we have the result that $\frac{\partial P_i^1(t)}{\partial \sigma} > 0$ for that specific set of parameters thus the decrease in σ_τ^2 will depress firm valuation. [††††]

A valuation decrease is the most probable outcome as g^c is drawn from a normal distribution; furthermore a price decrease will result in a significantly dominating set of cases. For example under risk neutrality, a variance of 0.15 and a technology horizon of 20 periods, the probability that the valuation shall decrease following t_1, subject to an increasing adoption profile, is higher than 93%.

We shall now evaluate the market value of a firm under the assumption that μ_τ does not change following t_1. This will provide us with an analysis for the most likely ex-

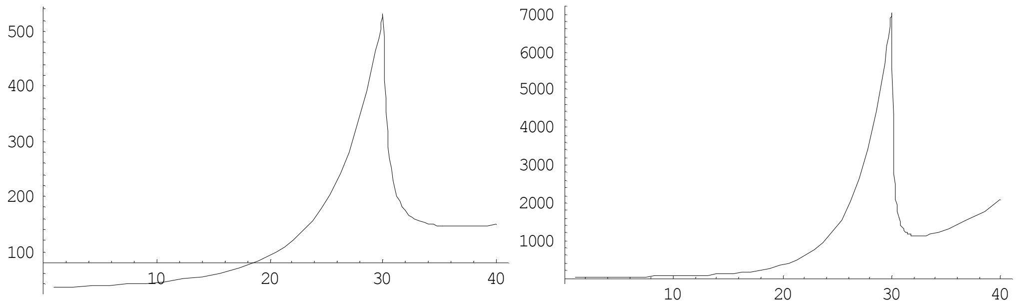
[§§§] Note that this is always the case if the utility function is at least *GSU(t_c)*

[****] Under risk neutrality the probability is exactly $\Phi(\frac{\min(T, t_c) * \sigma}{2})$

[††††] Valuation depression following t_1 due to a decrease in uncertainty will also occur when the adoption profile was initially monotonously increasing and then monotonously decreasing provided that $\hat{\theta}_{t1} > \mu_{g^c}(n_{t1})$ however the magnitude of the decrease will be of a smaller magnitude.

post scenario. This ex-post scenario does not evaluate the mean of a firm's market valuation but rather the most probable outcome of the valuation path. Under this assumption according to *Proposition 2* the value of the new technology firm will decline as σ_{τ}^{2} declines. The rate of decline in σ_{τ}^{2} and subsequently the new technology market firm will decrease faster as λ is smaller.

Figure 14 shows the market equilibrium value of two individual firms with different θ values, both graphs were simulated under the assumption that $ExPost\ \ g^{c} = E_{t1}(g^{c})$



θ=0.15 θ=0.05

Individual Firm Market Values

$T = 30,\ \ t_1 = 30,\ \ \sigma^2 = 0.1^2,\ \ \mu_{g^0} = 0.02,\ \ \mu_{g^c} = 0.15$ with $U(c) = \frac{c^{1-\alpha}}{1-\alpha}$ and $\alpha = 0.1$

Figure 14

Lemma 5

Increased technology adoption by firms, results in a faster information update process following t_1 thus $\frac{\partial P^{1}(t)}{\partial t \partial n} > 0 \quad for\ \ t > t_1$.

According to the information update procedure outlined in equation (4), when n is higher or λ is smaller, σ_{τ}^{2} is updated at a faster rate and the resulting expected variance of the growth parameter is decreasing at a faster rate. According to *Proposition 2* a faster change in variance would result in an even faster change in the mean of expected future dividends, resulting in a faster update to firm valuation.

How do network externalities impact firm valuations?

If the utility is *GSU*(t_c) then positive externalities, which affect the expected mean of the new technology growth distribution, will always weakly increase valuations as we approach $t_{1,}$ regardless of the degree of uncertainty. In the general case for some firms the overall long term impact of positive externalities on valuation may be ambiguous and depends on the shape of the externality and utility functions. For every given adoption level n_t, a positive externality results in a higher valuation for the pair (t,n_t); however in a dynamic setting the externality may increase adoption to a level which decreases the future expected marginal utility to such a level were it offsets the additional externality induced productivity increase for marginal firms.

Proposition 3

If the utility function is *GSU*(t_c) and some adoption has occurred prior to t_1 then:

The introduction of positive externalities:

a) Increases market valuation of adopting firms prior to t_1. [‡‡‡‡]

b) Most probably, induces a faster rate of decline in the market value of new technology firms following t_1.

Proposition 3(a) results from the monotone adoption profile (*Lemma 2)* and the fact that an increase in the mean of the expected new technology growth actually generates a relative decrease in uncertainty. Proposition 3(b) is a result of the increase in the number of adopting firms at t_1. Following *Lemma 5* we get the result that this induces a faster update of firm valuation post $t_{1.}$ It is important to point out that *Proposition 3(b)* does not imply that the market value of a specific adopting firm, post t_1 is necessarily lower, but that the rate of valuation change post t_1 is faster. *Proposition 3* suggests that, under specific conditions, positive network externalities induce a more dramatic boom and bust valuation pattern.

In this section we have demonstrated that, under the specified conditions, the most probable valuation path for a firm which has adopted the new technology is a sharp appreciation as we approach t_1 followed by a sharp decline. Even the best suited

[‡‡‡‡] This Proposition will not necessarily hold if network externalities impact the variance of the expected new technology growth.

technology firm with θ=0 will most probably follow this valuation path. Such a valuation path does not imply that technology adoption was 'wrong' for most firms, nor does it imply that the overall economic performance of the economy is always harmed by such a path as we shall further evaluate in following sections.

<u>The success probability of adopting firms</u>

Let us now evaluate the impact of this potential valuation path on different vintages of technology adopting firms. In this section we limit our analysis to the case of monotonously increasing adoption profile until t_1.

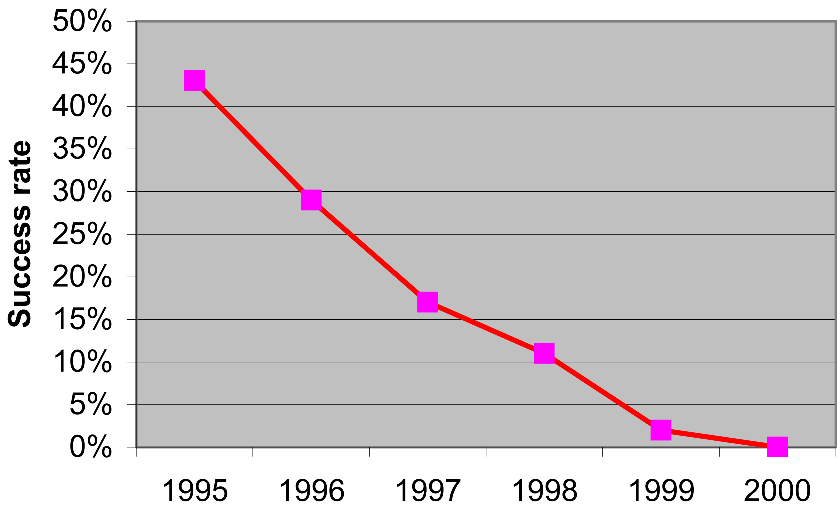
As we move closer to t_1, firms which are less suitable for the new technology, i.e. with higher θ, adopt the technology. The adoption decision for these firms is based on more distant profits which are more sensitive to the variance of the new technology advantage. If the decline in variance is not accompanied by a significant increase in ex-post μ_{g^c} the adoption value for these firms becomes negative. They regret the adoption of the new technology. Thus we get proposition 4:

Proposition 4

The probability that a firm is ex-post satisfied with its private technology adoption decision is negatively correlated with the firm's adoption decision date.

This result is a direct outcome of the adoption criteria in the model and the time sensitivity of firm value to new technology uncertainty. This sensitivity increases as more distant future profits were required to justify the technology adoption decision.

Figure 11 depicts some evidence from the .com bubble. The figure shows the ex-post, vintage success rate for consumer based internet firms as presented by Hendershott (2004) for this sub category. Common belief often attributes this phenomenon to the early mover advantage, as well as the inability to raise additional financing as the bubble crashed. These explanations are indeed part of the story , nevertheless our model support a much more direct explanation, as firms which adopt the technology closer to the innovation inflection point were 'less suitable' for the new technology, compared to the early adopters, thus more of these late adopters failed.



Success Rate for venture backed .Com Firms by initial financing vintage
Figure 15

Stock Markets and indexes

The total market value of new technology firms at time t is summarized by

$$(11)\ \ \widehat{P}(\hat{\theta},t) = \int_{\theta=0}^{\hat{\theta}} P_{\theta}^{1}(t) f(\theta)\ d\theta$$

Where $P_{\theta}^{1} \equiv P_{i}^{1} \quad | \ \theta_{i} = \theta$ and *f* is the PDF corresponding to *F*.

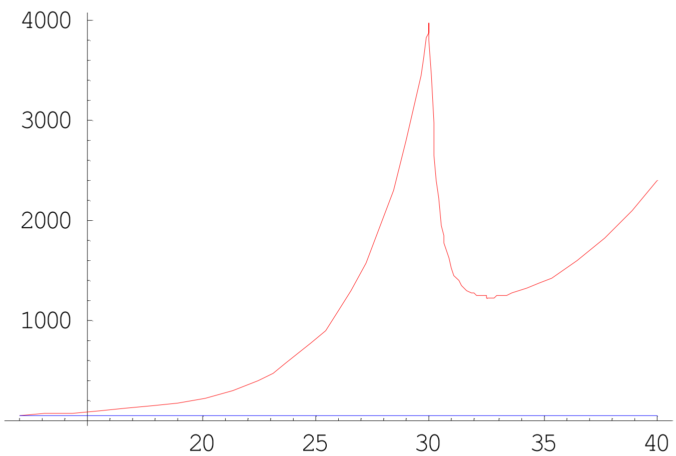
Without loss of generality we normalize the total number of firms in the economy to a unit of 1.

Under free entry and exit the new technology market index will be $\widehat{P}(\hat{\theta}_{t},t)/F(\hat{\theta}_{t})$. Under the assumption that post t_1 the adoption decision is binding, at least for some period after t_1, the new technology market index following t_1 shall be

$\widehat{P}(\hat{\theta}_{t1},t)/F(\hat{\theta}_{t1})$ which includes those firms which Ex-Post regret technology adoption but are bound to utilize it for some time following t_1. The old technology market index will be equal to the value of an individual old technology firm *P(t)* .

Figure 12 shows a simulated stock market indexes for new technology companies using the same parameters as in Figure 10. Simulation performed with no externality effect and a uniform *F*, under the assumption that $ExPost\ g^c = E_{t1}(\mu_{g^c})$. Obviously Figure 10 plots one possible outcome; however this is the outcome that is the most probable to occur for the simulated set of parameters.

A direct result obtained directly from Proposition 2 shows that a sharp decline in valuations following t1 is the most probable Ex-post scenario obtained for all sets of parameters where $\hat{\theta}_{t1} >> \mu_{g^c}(n_{t1})$. This is the typical result when adoption is monotonously increasing as we approach the new era date.



Stock Market Indexes

$T=30,\ t1=30,\ \sigma^2=0.1^2,\ \mu_{g^0}=0.02,\ \mu_{g^c}=0.15$ with $U(c)=\frac{c^{1-\alpha}}{1-\alpha}$ and $\alpha=0.1$

Figure 16

The next section evaluates the impact of the bubbly adoption and valuation path on post bubble productivity and long term growth.

VI. Production and Productivity

In this section we evaluate post bubble production and growth. We focus on those scenarios which produce a bubble like profile and evaluate the possible impact of network externalities on post bubble productivity. We evaluate the potential impact of uncertainty on innovation adoption and productivity and compare these results to a complete certainty benchmark.

We shall first quantify the expected total production and productivity after t_1, when the new technology begins to produce its benefits. We shall assume a monotonously increasing adoption profile up to t_1, as well as a binding adoption decision after t_1. These condition guarantee some degree of over adoption as well as full accounting for the over adoption costs.[§§§§] Our base line evaluation shall assume the most likely scenario, i.e. $ExPost\ g^c = E_{t1}(\mu_{g^c}))$.

Without loss of generality we assume s=1 and normalize D(t_1) =1 . For simplicity of notation $\bar{\theta} \equiv \hat{\theta}_{t1} \quad , n \equiv n_{t1}$. Equation 12 describes economy production on the equilibrium path for a general distribution F. Equation 13 is the explicit equivalent for the special case of a uniform distribution of θ.

$$(12) \qquad D(t_1 + \tau) = E_t\left[\int_0^{\bar{\theta}} e^{(g^0+g^c(n)-\theta)\tau} f(\theta)d\theta + \int_{\bar{\theta}}^{1} e^{g^0\tau} f(\theta)d\theta\right]$$

$$(13) \qquad D(t_1 + \tau) = \frac{e^{(\bar{g}^0+g^c)\tau}}{\tau}[1 - e^{-\bar{\theta}\,\tau}] + (1-n)e^{\bar{g}^0\tau}$$

$$\text{Were } \bar{g}^0 = \mu_{g^0} + \frac{\sigma_{g^0}^2}{2}$$

Equation 14 describes the per period production change resulting from technology adoption. Equation (15) describes the production increase at t_1+1 for the special case of a uniform θ distribution.

[§§§§] Relaxing this assumption will reduce over-adoption costs for a given over adoption value, however if we allow firms to revert back to the old technology following a certain period this will modify the adoption decision variable such that overall adoption would further increase as the cost from "wrong" adoption is reduced.

$$(14)\quad DiffD(t_1+\tau)=E_t\left[\int_0^{\bar{\theta}}(e^{(g^0+g^c(n)-\theta)\tau}-e^{g^0\tau})f(\theta)d\theta\right]$$

$$(15)\quad e^{\bar{g}^0}(e^{g^c(\theta)}(1-e^{-\bar{\theta}})-\bar{\theta})$$

If there is no externality and no uncertainty regarding g^c production then productivity post t_1 will always increase. This is a direct result of the fact that θ is endogenously selected and only firms with $\theta \leq g^c$ will adopt the technology.

If uncertainty exists, under monotonously increasing adoption we shall have a result which incorporates over adoption as $E(\bar{\theta}) > \mu_{g^c}(\bar{\theta})$. Production and productivity at t_1+1 depend on the relative over adoption compared with actual $g^c(\bar{\theta})$.
Production will increase at t_1+1 as long as the following condition is satisfied:

$$(16)\quad g^c(\bar{\theta}) > \ln\bar{\theta} - \ln(1-e^{-\bar{\theta}})$$

This condition allows for significant over adoption to exist along side an increase in overall productivity at the innovation utilization date. In a robust range of values a sharp productivity increase will occur immediately following t_1, this productivity increase will generally coincide with the strong deflation of the stock market valuations for new technology firms. Such timing and sequence is indeed similar to the actual US market and productivity data detailed earlier. If production increases at t_1+1 it is expected to continue and marginally increase further as the relative production volume of those new technology firms which are most adapted to the new technology dominates an increasingly growing portion of the economy.

Limiting the maximum market share of an individual firm may generate a more realistic outcome regarding long term productivity. Without such a size cap productivity will continue to marginally increase until t_1+t_c, a result which we do not expect to find in the empirical evidence.

The impact of uncertainty and externality on productivity and long term growth.

Under the conditions described, uncertainty induces increased adoption. In the presence of externalities this increased adoption impacts the magnitude of technology growth. At the same time increased adoption, most probably, generates over adoption, thus some firms which adopt the technology would have liked to change their decision ex-post. We now attempt to quantify the overall long term impact of this process. We compare the most probable production outcome of two different information scenarios. In the first, adoption decisions are only taken based on the true, fully known, innovation parameters while in the second the market follows the uncertainty induced bubbly process described under our framework.

For simplification of the exposition we assume $\theta_i \sim U[0,1]$, thus $n = \overline{\theta}$.

Under the assumptions leading to a monotonously increasing adoption path up-to t_1, The mean of $\overline{\theta}$ under the incomplete information process will always be higher than the complete certainty / delayed adoption scenario. Thus we may define the following:

$$\overline{\theta} = \overline{\theta}_b + \theta_\Delta$$

$$g^c(\overline{\theta}) \equiv g = g(\overline{\theta}_b) + g_\Delta \equiv g_b + g_\Delta$$

Subscript b denotes the results under the certainty path.

We shall now compare the outcome of the natural “bubble like” process to the full certainty scenario, without loss of generality we assume D(t_1)=1. As in the previous section we assume that the technology adoption decision at t_1 is binding for the evaluated period. This will incorporate in the analysis all over adoption costs for firms committing to the new technology at t_1.[*****]

Let w\{t) be the period $t1+t$ difference in expected production between these two scenarios.(*i.e.* $E[D(t_1+\tau) - D_b(t_1+\tau)]$)

[*****] Relaxing this assumption will reduce over-adoption costs for a given over adoption value, however if we allow firms to revert back to the old technology following a certain period this will modify the adoption decision variable such that overall adoption would further increase as the cost from “wrong” adoption is reduced.

$$(17)\quad w(\tau)=\frac{e^{(\bar{g}^0+g_b)\tau}}{\tau}[e^{g_\Delta\tau}(1-e^{-\bar{\theta}\tau})-(1-e^{-(\theta_b)\tau})]-\theta_\Delta e^{\bar{g}^0\tau}$$

The value of $\int_{\tau=0}^{T} w(\tau)d\tau$ provides a measure for the overall T period production change. While the value of $\int_{\tau=0}^{T}\rho(t_1,\tau)w(\tau)d\tau$ provides a measure of aggregate T period welfare change.

We evaluate the explicit relative performance of the two scenarios regarding relative production and productivity at t_1+1. Obviously there are cases where the bubble like scenario is inferior at t_1+1 but the overall result over T periods is superior. However, this superiority depends on the exact nature of the utility function and the inter-temporal preferences of the market. A superior t_1+1 outcome for the bubbly scenario is a sufficient condition for overall superiority regardless of the exact utility function or inter-temporal preferences.

Under the above assumptions Period t_1+1 production difference reduces to:

$$(18)\quad e^{g_b}(e^{g_\Delta}-1)+1-e^{g_\Delta-\theta_\Delta}-\theta_\Delta$$

It is clear that: $\frac{\partial w(1)}{\partial g_\Delta}>0$, a stronger positive externality provides for increased productivity. It is interesting to note that $\frac{\partial w(1)}{\partial g_\Delta \partial g_b}>0$, The higher the new technology improvement baseline, the stronger the externality impact on relative productivity.

Regarding the impact of the added adoption, under the uniform distribution assumption, $sign(\frac{\partial w(1)}{\partial \theta_\Delta})=sign(g_\Delta-\theta_\Delta)$. The derivative with respect to adoption for any $\theta_\Delta>g_\Delta$ is negative. This is the expected case under the assumption that market participants have knowledge of the externality function and adoption rate at any given time. This result is derived directly from the fact that under uncertainty the new growth variance enters the adoption criteria equations with a positive sign. When no externality exists $g_\Delta = 0$ and any value of θ_Δ Results in a negative partial derivative, thus we get proposition 5:

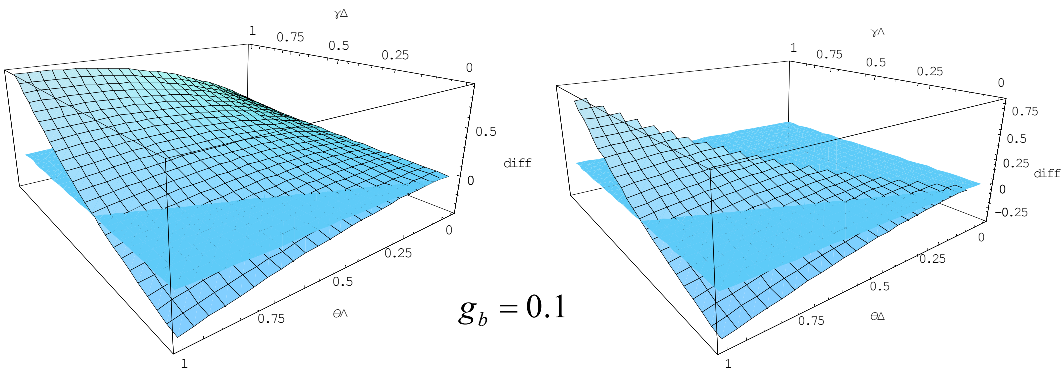
Proposition 5

If the adoption path is monotonically increasing and innovation adoption externalities do not impact production then:

a) The 'bubble' like process, induced by uncertainty, will, most likely, reduce long term production and growth.
b) If the utility function is SGS then a higher degree of innovation uncertainty will decrease long term production and productivity.

As a direct result from *Proposition 1* we get $\hat{\theta}_{t1} > \mu_{g^c}(n_{t1})$, For the specific case without externality this translates to $\theta_\Delta > g_\Delta = 0$ which generates reduced production in equation (18). Under SGS utility we get $\dfrac{\partial V(t1)}{\partial \sigma} > 0$ thus $\dfrac{\partial \hat{\theta}_{t1}}{\partial \sigma} > 0$ resulting in Proposition 5b.

Figure 17 plots the relative performance of period 1 productivity of the uncertain bubbly process compared with the synthetic certainty equivalent. The left graph in Figure 17 depicts the full range of θ_Δ while the other depicts the results under the constraint $\theta_\Delta > g_\Delta$.



Relative performance of the uncertainty induced bubbly scenario compared to synthetic certainty

Figure 17

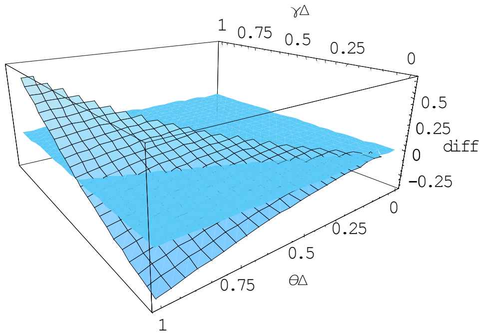
Proposition 6

If the adoption path is monotonously increasing and innovation adoption externalities positively impact new technology output then:

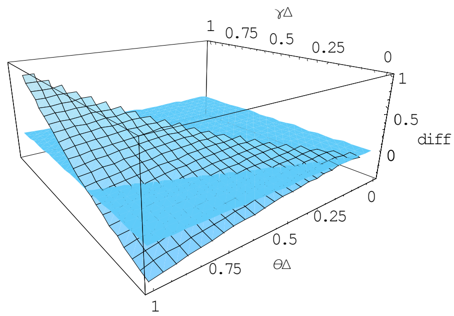
a) The impact of the 'bubble' like process on productivity is ambiguous and depends on the relative strength of the positive externality process and increased adoption.

b) Given any positive impact of adoption on innovation, a higher new technology productivity baseline (g_b) supports a higher probability for improved productivity under the uncertainty induced bubbly process.

Figure 18 shows the period t_1+1 production comparison for two different values of g_b. The simulated impact of g_b on the possible results is clear. A higher g_b increases the range of parameters which produces superior results in the uncertain bubbly scenario.



$g_b = 0.02$



$g_b = 0.2$

Relative performance of the uncertainty induced bubbly scenario compared to synthetic certainty for different values of g_b

Figure 18

If the externality is sufficiently strong, a preferred policy should support non intervention allowing the bubbly process to push the market into a higher level of growth.

This result is a direct interpretation of the partial derivatives of equations (17) & (18). The more innovative the technology, the higher are the chances that the overall outcome of the uncertainty induced market 'bubble' produces a superior result.

If we refer back to the historic episodes which served as a motivation to this paper, it is now widely accepted that both involved a significant technology paradigm change which among other features, included a significantly accelerated growth path for those companies implementing the new technology. In addition both technologies are inherently network technologies which provide improved functionality and utility as the network grows, thus a high level of positive externality was a basic feature of both technology revolutions. In the framework of our model we would categorize both of these historic accounts with high uncertainty, a high level of baseline productivity improvement and a strong externality reaction. In the scope of our model all of these features support a large bubble with a high probability for ex-post growth superiority for the bubbly path.

VII. Conclusion

In this paper we studied the impact of uncertain innovation on the concomitant time path of stock market valuations, innovation adoption and the resulting productivity and growth. We specified the conditions which may produce valuation and adoption profiles often associated with market 'bubbles'. We analyze results in a setting which incorporates network externalities and show that when externality forces are weak, the most probable outcome under these conditions includes a valuation 'bubble', over adoption and wasted resources. However; if a significant innovation is prone to network effects it is more probable that the "bubbly" process generates post bubble superior growth and productivity. In our model uncertainty and externalities may amplify market valuations as well as adoption. In turn, increased adoption not only impacts long term productivity but may also generate a more dramatic bubble behavior, with a higher peak and a faster decline.

Our results are consistent with technology adoption, stock market behavior and productivity data series associated with the internet bubble and may be used as a parsimonious explanation for the unprecedented US productivity growth figures documented after the collapse of the internet bubble. Our framework supports the claim that the magnitude of post bubble US productivity growth may have actually been amplified as a result of the preceding valuation pattern. If indeed the forces described were dominant in propelling adoption and productivity we may expect to see continued improvements in productivity during the next few years.

Attaching a productive role to the bubbly process itself may also have interesting implications for policy makers; A policy maker anticipating the possibility of a bubble like scenario may wish to intervene and prevent such a possible outcome, however we show that when the cause of the bubble is a significant, externality intensive, innovation, non intervention, even in face of what seams to be ‘irrational exuberance’, may sometimes be the preferred path, and that in these cases laissez-fair policy holds both under the mean as well as the most probable outcome.

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