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Technology Acceleration: Model and Evidence

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Abstract

This paper investigates the occurrence of 'technology acceleration' across a range of information technologies. The prospect of technology was broached by Gordon Moore of Intel in 1965. His anecdotal 'law' – i.e. performance / price doubles every 18 months – has become received wisdom in many technology industries. Gilder popularized it as Moore's law and proposed Gilder's law and a number of such 'laws' - reflect underlying social and networking phenomena in research and development. These 'laws' appear to hold for long periods of time, and specific technology markets may be characterized by their specific "technology acceleration coefficients". Technology acceleration is related to the broader economic study of what are called hedonic pricing methods, which themselves are approaches to identifying shadow values. The hedonic pricing literature attempts to infer demand for product characteristics (such as performance) from market prices. This research review the hedonic pricing literature for computers, extends the existing literature for a broad range of computers and information technologies, and proposes technology-specific dynamic measures of price-performance change that is robust.

Keywords

Hedonic pricing, computers, productivity paradox

1. Introduction

Gordon Moore's (1965) articulation of a 'law' governing growth in computing performance was popularized by Gilder and has become received wisdom in many technology industries (Gilder 1999, Gilder 2000 & Moore 1965). For instance, the microprocessor industry uses Moore's law as a benchmark to follow for its R&D efforts. Computer manufacturers Dell and Gateway use internal models based on Moore's Law that completely depreciate inventory over a three-month period. Microsoft expenses all software development costs right away.

Gilder (1999, 2000) suggested that a similar 'law' is present for communication technology. This is the Gilder's law. In fact, it is a common belief that similar laws as Gilder's and Moore's govern the change of performance/price of technologies over time. Each of them is widely accepted and was proposed based on the observations of respected individuals. They represent non-linear relationship that has grown to economic importance in knowledge-intensive businesses. Westland provides a summary of the research in *Valuing Technology* (Westland 2002) and terms this phenomenon as technology acceleration. This notation will be used in this research.

Technology acceleration has significant strategic impacts on firms. Traditional accounting fails to handle such non-linear relationships. With accelerating performance/price of technology, complete depreciation of technology assets is likely to happen in months or even weeks. In traditional accounting, all these within-one-year depreciations are considered to be one time expenses on a yearly basis. This could result in sub-optimal operations and management decisions. Incorporating technology acceleration into the financial valuation of technology products and knowledge-intensive businesses could help a lot.

The remaining sessions of this paper go as follows. Session 2 gives a brief discussion on the exponential model of technology acceleration and its foundations. Session 3 describes the data collection process. Session 4 presents and discusses the results. Session 5 concludes and points out implications and future directions.

2. Theory

The study of technology price-performance over time is related to the broader economic study of what are called hedonic pricing methods, which themselves are approaches to identify shadow values. The hedonic pricing literature attempts to infer demand for product characteristics (such as performance) from market prices. Automobiles, property and houses are common subjects of such studies. In theory, we can infer the marginal value (price) of each qualitative characteristic from the associated partial derivatives. For example, the price of a car reflects its underlying characteristics – transportation, comfort, style, luxury, fuel economy, etc. Then we can value individual characteristics of a car or other good by looking at how the price people are willing to pay for it changes when the characteristics change. (Epple 1987)

It is common to observe exponential relationships between prices and qualitative factors in hedonic pricing. This is because the particular measures tend to reflect perceived utility or productivity of a technology over time. Otherwise, consumers

would be likely to see the metric as being irrelevant. Debates over the best metric – e.g. Whetstone, Dhrystone, Rhexstone, Gabriel, SPECmark, LINPACK and so on, in measuring CPU performance – are typically couched in terms of appropriateness to the uses to which specific groups of consumers commonly put the product. It is common for our physical perceptions to respond logarithmically; e.g. our eyes and ears perceive intensity of light or sound logarithmically, which gives their perception a range of scales that is hard to duplicate in machines. Similarly, human perceptions of quality or other factors of human or social importance are likely to be logarithms. If this is the case, then our perception of price for a given quality level – i.e. the hedonic price – are likely to grow exponentially over time, simply because of the way that we are measuring / perceiving that particular quality.

Moore's and Gilder's laws suggested that values of technology changes exponentially rather than linearly over time. Take Moore's law. Computing performance per price measured as MIPS/cost doubles every eighteen months or 1.5 years. Let p be the performance metric per price, i.e. MIPS/cost. Then the value of p at year t after year 0 is given by:

$$p_t = p_0 \cdot 2^{\left(\frac{t}{1.5}\right)}$$

Linearizing the above:

$$\ln p_t = \ln p_0 + t \left(\frac{\ln 2}{1.5} \right)$$

$$\Rightarrow \ln p_t = \ln p_0 + 0.462t$$

$$\Rightarrow p_t = p_0 e^{0.462t}$$

Moore's law of doubling of performance/price of CPU technology in 18 months (i.e. 1.5 years) thus implies a stable annualized technology acceleration coefficient $a = \ln 2 / 1.5 = 0.462$. This implies an annual growth rate of around 40%, which is reasonably accurate for CPU chip performance. Table 1 shows that this performance acceleration rate is reflected in the finished PC market as well. The performance of finished PC depends on a variety of technologies in addition to the CPU; anyone of these can be a bottleneck to improvement in performance. Thus the rate of PC performance growth is generally less than 40% annually (in the range of 20% to 40%, approaching 40% in recent years).

Authors	Time Period	Prices: Annual Rate of Change
Chow (1967)	1960-65	21%
Triplett (1992)	1953-72	27%
Cole, et al (1986)	1972-84	19%
Cartwright (1986)	1972-84	14%
Gordon (1971)	1951-84	22%
Cohen (1988)	1982-87	26%
Berndt and Grilliches (1993)	1982-89	24%
Berndt, Grilliches and Rappaport (2000) (Laptop PC)	1989-92	24%
Berndt, Grilliches and Rappaport (2000) (Desktop PC)	1989-92	32%
Nelson, Tanguy and Patterson (1994) (Desktop PC)	1984-91	23%

Authors	Time Period	Prices: Annual Rate of Change
Chwelos (1999) (Desktop PC)	1976-83	34%
Chwelos (1999) (Laptop PC)	1976-83	18%
Berndt and Rappaport (2000)	1983-89	18%
Berndt and Rappaport (2000)	1989-94	32%
Berndt and Rappaport (2000)	1994-99	39%
Aiscorbe, Corrado and Doms (2000) (Desktop PC)	1994-98	31%
Aiscorbe, Corrado and Doms (2000) (Notebook PC)	1994-98	26%
BEA price index (Landefeld and Grimm, 2000)	1994-98	32%

Table 1: Prior Research and Findings in Computer Technology Acceleration

In a similar vein, Gilder's law of tripling of performance/price of communication technology in 9 months (i.e. .75 year) implies a stable annualized technology acceleration coefficient $a = \ln 3 / .75 = 1.469$. Knowledge economy presents numerous examples of highly non-linear scaling in costs and benefits. This non-linearity results from the growing complexity of production and marketing processes.

The Research Model

In general, the exponential function form of technology acceleration is:

$$p_t = Ae^{a^*t}$$

where p_t is the technology performance per price at time t , A is a constant, and a is the technology acceleration coefficient.

There are several properties worth noting with respect to technology acceleration coefficients. First, they are defined on specific performance metrics. The ones widely accepted and used by the market are likely to affect prices most and are good choices. For CPU, it is clock speed in MHz. For communication technology, it is switching cycles per second.

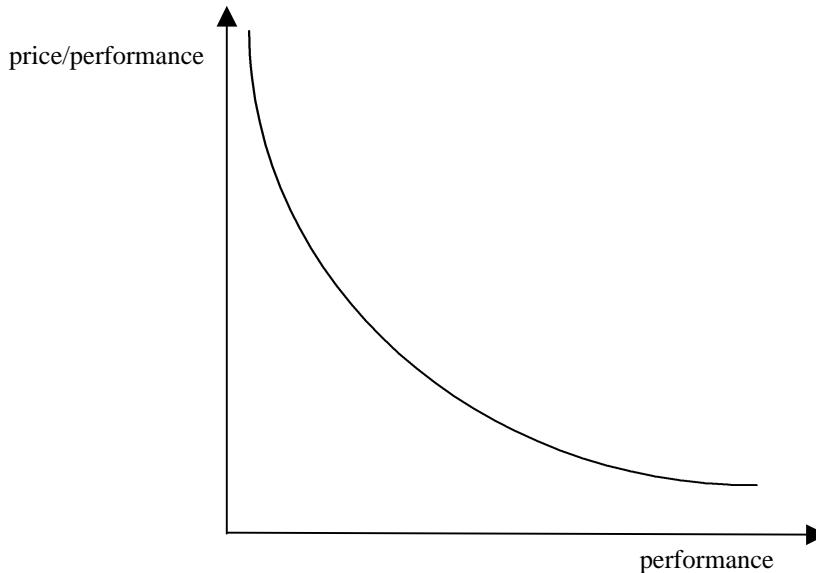
Second, technology acceleration coefficients are platform independent. The only thing required is to have consistent performance metrics across platforms. In computing, if we use MIPS (million instructions per second) as the performance metric, Moore's law is valid back to 1930s and covers mechanical, vacuum tube, transistor and VLSI platforms (Moravec 1990).

Third, technology coefficient coefficients partly reflect rate of progress in the evolution of the platforms. The number of researchers and laboratories, the commercial significance of the technology and the difficulty of mastering the technology all determine the rate of technology acceleration.

Technology Acceleration as a Restricted Hedonic Pricing Model

To investigate the over-time changes of performance/price of a technology product, we need to understand the relationship between price and performance.

View the amount of performance as the demand quantity. A price/performance for a certain technology product is then the unit price we usually use in a demand function. By the law of demand, the more technological performance bought in one time, the lower the price/performance (higher performance/price) will be. And there will be one price/performance for each product with different performance level. A 1 GHz CPU will have a lower price/performance in terms of dollar per clock speed than a 512 MHz CPU.



The inverse demand function at any particular time period is illustrated as above. It has the following functional form:

$$\frac{\text{Price}}{\text{Performance}} = \mathbf{g} \cdot (\text{Performance})^{\mathbf{q}}$$

$$\Rightarrow \text{price} = \mathbf{g} \cdot (\text{performance})^{\mathbf{b}}, \text{ where } \mathbf{b} = \mathbf{q} + 1$$

This is simply a hedonic price equation with performance as the quality attribute traded implicitly in the market. Linearizing it will give:

$$\ln \text{price} = \text{constant} + \mathbf{b} * \ln \text{performance}$$

Suppose at time t there is a technology product that have j important performance dimensions affecting its market price, p_t . The level of performance dimension j of that particular technology product at time t is given by Q_{ij} . Using the traditional hedonic pricing method, we have:

$$\ln p_t = \text{constant} + \sum_j \mathbf{b}_j * \ln Q_{ij}$$

Traditionally, hedonic price method is used to construct quality-adjusted price index by taking time as an independent dummy variable T_t , which equals one at time period t , and this gives:

$$\ln p_t = \text{constant} + \mathbf{a}_t * T_t + \sum_j \mathbf{b}_j * \ln Q_{ij}$$

$$\Rightarrow \ln p_t = \text{constant} + \mathbf{a}_t + \sum_j \mathbf{b}_j * \ln Q_{tj} \text{ as } T_t = 1$$

By putting two restrictions into the general hedonic price equation above:

$$\begin{cases} \mathbf{a}_t = -\mathbf{a} * t \\ \mathbf{b}_j = 1 \end{cases}$$

$$\Rightarrow \ln price_t = \text{constant} - \mathbf{a} * t + \sum_j \ln Q_{tj}$$

$$\Rightarrow \ln price_t = \text{constant} - \mathbf{a}t + \ln Q_t \text{ by putting } Q_t = \prod_j Q_{tj}$$

$$\Rightarrow price_t = Ae^{-\mathbf{a} * t} Q_t$$

$$\Rightarrow p_t = Ae^{\mathbf{a} * t} \text{ as } p_t = \text{unit performance per price} = \frac{Q_t}{price_t}$$

, which gives the exponential model of technology acceleration.

The interpretation of the two restrictions is straight forward. The first restriction is the exponential growth of performance-price over time, i.e., the content of the technology acceleration model.

The second restriction is a requirement of the performance metric. The right performance metric to be used in the technology acceleration model will have unit price elasticity. This requirement is a weak one. If the estimated price elasticity is not one, the performance metric being used can be easily adjusted by a suitable scaling factor. This scaling factor is just the estimated price elasticity (the slope coefficient) of the performance dimension concerned.

3. Data Collection

We obtain secondary price data of technology products from a Hong Kong trade journal, *PC Buyer* (2002). Hong Kong establishes world-wide prices of computers and peripherals because nearly 100% of components (made primarily in South China and Taiwan) are sourced through Hong Kong. Out of all global price listings, Hong Kong prices for computer hardware will tend to be the least biased by logistics and local retailing considerations, because the industry sources through Hong Kong. Motherboards and chipset industries are centered in Taiwan and increasingly mainland China, and ordered through Hong Kong firms; disk drives, cabinets, keyboards, and other peripherals are produced almost exclusively in Guangdong province by Hong Kong owned firms. Local variances from the Hong Kong prices are likely to result from logistics, retailing, transport, taxes and duties, and other country-specific effects. Our use of Hong Kong prices eliminates these confounding factors from the data up front. *PC Buyer* is a weekly publication. It publishes street prices of technology products. The prices are supplied by vendors/retailers or obtained directly from shops. Besides prices, it also reports other relevant product information like brand and performance. Data are available back to mid 1997.

To run a test of the technology acceleration phenomenon, we collected 22 to 28 weeks of performance and price data of 6 technologies from the end of 2001 to around April or May of 2002. Performance metrics chosen for technology are based on what is

important in consumers' product comparison. All performance data is available from the *PC Buyer* price list. This is reasonable as what is in print for comparison is mostly likely what the market concerns most and reflects market reality.

Clock speed and rotation speed are the most important performance metrics used in reflecting values for CPUs and CDROM drives respectively. Commercially, CPU performance is reflected by having a clock speed of, say 1GHz or 512MHz. CDROM drives are advertised as rotating at speeds of 52x or 16x. The same applies when we choose storage amount as the performance metrics for nonvolatile and volatile RAM.

For printers and monitors, things are a little bit more complicated. Both of them have more than one important performance metrics commercially. To handle this, we use a composite measure for each of them.

The one for printers is resolution multiplied by printing speed in ppm. At the same printing speed, higher resolution translates into better performance and higher values. At the same resolution, faster speed is more valuable. Hence, a composite measure derived by multiplying resolution and rotation speed together is a good choice as the performance metric of printers.

To represent the performance metric of monitors by a single number, we first multiply the screen size, the highest resolution supported and the screen refreshing frequency together. The composite measure is then given by dividing the resulting number by the point size. This is credible as the market values bigger screen, higher resolution, higher refreshing frequency and smaller point size whenever possible. Table 2 summarizes the performance metrics and time period coverage for the 6 technologies.

Technology	Performance Metrics	Time Period Covered
CPU	Clock Speed (in MHz)	2001/10/31 – 14/5/2002
CDROM	Rotation Speed	2001/10/31 – 23/4/2002
Printing	Resolution * Printing Speed (ppm)	2001/10/31 – 23/4/2002
Nonvolatile RAM	Storage Amount	2001/10/31 – 23/4/2002
Volatile RAM	Storage Amount	2001/10/31 – 23/4/2002
Monitor	Size * Resolution * Frequency / Point Size	2001/10/31 – 23/4/2002

Table 2: Performance Metrics & Time Period Coverage

By observing the data published by *PC Buyer*, there are non-performance factors that will affect the price comparison by consumers. Those non-performance factors fall into two categories. One is brand. In the CPU market, Intel is the giant and has significant brand value in consumers' minds. The other is type. Most categories of technology can be divided into different types that charge very different prices. For instance, laser printers are more expensive than ink printers even if they have the same resolution and printing speed. They are both printing technology, but based on different mechanism to print and give different qualities from consumers' viewpoint.

Thus, we use dummy variables to control those factors. For each week, data is collected for every type or brand of technology whenever possible. Table 3 summarizes dummy variables used and number of data points available.

Technology	Dummy Variables	# Weeks	# Data Points
CPU	Intel or non-Intel	28	56
CDROM	CDROM or DVROM or CDRW	24	72
Printing	Laser printer or Ink printer	24	48
Nonvolatile RAM	Flash Memory or Flash Card or Flash Drive	22	49 ¹
Volatile RAM	SDRAM or DDRAM or RDRAM	25	75
Monitor	Monitor or LCD or VIS	25	75

1: There are 1 week with only flash memory prices, 8 weeks with only flash card prices and 2 weeks with only flash memory and card prices.

Table 3: Control Variables, Number of Weeks and Number of Data Points

4. Results

In order to apply OLS regression formulae, we linearized the exponential research model by taking natural log and add relevant dummy variables. The research model becomes:

$$\ln(\text{performance} / \text{price}) = \text{constant} + \mathbf{b} * \text{dummy variables} + \mathbf{a} * t$$

where \mathbf{a} is the technology acceleration coefficient and t is the time period.

From the regression results, all prove significant at almost any level of reliability. In light of the regression results, the proposed exponential functional form of performance/price of technologies over time appears valid and robust.

Five out of six technologies (the one exception is video display monitors, where technology evolves too slowly for the short duration of this analysis to be reliable) have significant t values for the time coefficient. With one exception (volatile RAM), the t values are positive. The performance/price of CPU, CDROM, printing and nonvolatile RAM technologies increase significantly over time.

By taking a closer look, we see that the insignificant t value for monitor technology and the negative significant t value for volatile RAM technology do not cause problems.

The time coefficient of monitor technology is 0.00388. This implies that it takes around 3.4 years to double the performance/price of monitor technology. This slow rate of technology acceleration could be due to the technology being very mature. With only 25 weeks data and such slow rate of acceleration, the insignificant t value, though positive, should be expected. The good fit and validity of the model ($R^2=89.73\%$ and a 99% confidence level significant F value) assure us that the technology acceleration model is right for monitor technology.

With a negative time coefficient, volatile RAM technology is experiencing technology deceleration in the time period covered. In other words, there is a price surge given the same performance. It is the result of recent market conditions and memory availability. Volatile memory prices (represented by SDRAM, DDRAM and RDRAM) had been rising since November 2001. On one hand, excess factory capacity is getting soaked up.

On the other hand, demand for DDR RAM and SDRAM boosted since December 2001 when Intel released a chipset, the 845, that allowed PC makers to match Pentium 4 chips with the faster memory (CNET News.com 2002). Over a long enough time period, the effect of technology acceleration will dominate. In fact, volatile memory prices experienced a general price drop during the last few years.

The coefficients of determination (i.e. R square) for the 6 technologies range from 31.95% to 89.73%. The explanatory power of the proposed model is impressive. The times required to double the performance per price range from about half year to three and a half year. The doubling time for CPU technology is 1.4 year. This is very close to 1.5 year and re-confirms the Moore's law. Table 4 below summarizes the results.

Technology	Annualized Acceleration coefficient (regression coefficient) ³	# weeks to double ⁴	t Value	Pr > t	F Value	Pr > F	R ² (%)
CPU	0.48672 (0.00936)	74 (~1.4 yrs)	1.99	0.0518	12.44	< .0001	31.95
CDROM	1.3754 (0.02645)	26 (~ 0.5 yrs)	4.52	< .0001	156.65	< .0001	87.36
Printing	1.7238 (0.03315)	21 (~ 5 months)	1.87	0.0683	27.73	< .0001	55.20
Nonvolatile RAM	1.44924 (0.02787)	25 (~ 0.5 yrs)	10.38	< .0001	77.84	< .0001	83.84
Volatile RAM	-1.27296 (-0.02448 ¹)	28 ² (~ 7 months)	-6.18	< .0001	41.38	< .0001	63.61
Monitor	0.20176 (0.00388)	179 (~ 3.4 yrs)	0.95	0.3429	206.74	< .0001	89.73

1: negative acceleration coefficient implies that the performance/price of this technology decelerates over time.

2: this is the time required to halve the performance/price.

3: The annualized acceleration coefficient is computed by $\hat{a} * 52$ where \hat{a} is the estimated time coefficient from the regression equation $\ln(\text{performance} / \text{price}) = \text{constant} + \mathbf{b} * \text{dummy variables} + \mathbf{a} * t$

4: The weeks to double = $\ln(2) / \hat{a}$

Table 4: Summary of Results

To check whether the regression model converge with increasing number of observations, we divide the data sample into 3 sets. One set contains about one third of the total observations, another contains two third while the remaining one has all available observations. The regression results support a convergence to a robust and stable set of technology acceleration coefficients. The F values and t values for the six technologies all increase in general with increasing number of observations. Though the t value of monitor technology does jump a little bit, it is acceptable given its slow rate of technology acceleration, implying that we need a larger time interval to estimate the coefficient than was applied in this research.

There are two evidences for the convergence of the regression. First consider the t value. A larger t value together with a smaller standard error makes the corresponding regression coefficient more significant. For *all six* technologies, the standard errors decrease as number of observations increase. Consequently, the technology acceleration coefficients (the regression coefficient for time) become more significant with more observations. This is an evidence of convergence.

Another evidence of convergence comes from the F values. The larger the F value, the more valid the underlying regression model is. When we add more observations to the regression, the F values for the 6 technologies increase without exception. Actually, all F values are significant at 95% confidence level even for the dataset with smallest number of observations.

The regression does converge with more and more observations. The six technologies do follow the exponential model of technology acceleration. Table 5 summarizes the change of statistics with increasing number of observations.

Technology	t Value [#weeks/data points]			F Value		
CPU	0.3[11/22]	1.13[20/40]	1.99[28/56]	3.65	7.74	12.44
CDROM	-0.22[8/24]	2.29[16/48]	4.52[24/72]	25.99	79.10	156.65
Printing	-0.34[9/18]	0.99[18/36]	1.87[24/48]	6.86	16.96	27.73
Nonvolatile RAM	4.53[15/25]	7.39[19/37]	10.38[22/49]	14.24	37.55	77.84
Volatile RAM	-5.32[17/51]	-6.42[21/63]	-6.18[25/75]	44.40	47.40	41.38
Monitor	0.74[9/27]	-0.52[17/51]	0.95[25/75]	128.43	160.07	206.74

Table 5: Change of Statistics over time

5. Conclusion and Discussion

The results of our tests support an exponential form for technology acceleration, consistent with Moore's and Gilder's 'laws' (which heretofore have only been anecdotally supported). Our results for monitors and volatile RAM technologies were not as convincing, but we felt this was due to the short duration of the sample. Future research will extend the sample time period in attempt to estimate results for these technologies. Results for monitor technology are distorted by its very slow technology acceleration rate together with insufficient number of data points while that of volatile RAM technology are affected by recent market conditions and supply availability.

The explanatory power of these 'laws' appears quite high, indicating robust external validity. The time periods over which there is a doubling of performance per price range from about half year to three and a half years. For CPU technology, we verified and confirmed Moore's law. When we divide the data sample into 3 sets of different number of observations, the exponential model of technology acceleration shows evidence of convergence. We plan to run future tests over the whole time period back to mid 1997.

The performance/price of technology does increase exponentially over time. There are three properties worth noting with respect to the technology coefficient. First, they are defined on specific performance metrics. Second, they are platform independent as long as we have consistent performance metrics. Finally, they partly reflect rate of progress in the evolution of the platforms.

At some point, the development of technology will accelerate so substantially that there is a qualitative change in our management of technology investment. For example, we might ignore the cost of added bandwidth, because it is trivial. A claim that has been made repeatedly over the past decade is that new information and communications technologies, made possible by the Internet and other networks present such a radical quantitative improvement in speed and efficiency, that typically the social, political, technical or economic effects are *qualitative*. This observation has been offered repeatedly by *Amazon.com* founder Jeff Bezos (echoing the precepts of Joseph Stalin) arguing "evolution takes place in leaps, not gradually, where one passes suddenly from a succession of quantitative changes to a radical qualitative change – these sudden qualitative changes are revolutions". The quantitative leaps in

performance thrust us by pervasive computer and communications networks provide the basis for our current post-industrial ‘revolution’.

In the context of our prior arguments, we can see that the ‘revolutionary’ point at which a technology becomes ‘free’ is dictated by the acceleration coefficient of the technology. If we assume a ‘materiality’ (i.e. uncertainty) of around 5% for our accounting estimates, then performance can be considered ‘free’ when it drops below 5% of its current value.

In order to effectively decide whether to invest – either buy or make - in rapidly changing technologies, managers need to understand technology acceleration and its impact on businesses. Exponential depreciation of technology assets raises challenges to traditional accounting, because most technology investments are likely to depreciate in less than one accounting cycle, given the technology acceleration coefficients suggested in the research. Neglecting technology acceleration is likely to result in dramatically overvalued technology assets. This can lead to sub-optimal decisions in R&D planning and outsourcing decisions.

Technology acceleration fails traditional accounting processes and changes the time horizon for managerial decision-making. If the time value of money and the time sensitivity of risk-prone decisions are important, then technology acceleration demands a finer division of time – both in terms of management and accounting. We need to think in terms of month or days, instead of years, which is the most common accounting cycle. Noble laureate Robert Merton proposed continuous time financial modeling describing models that support the decisions of managers with access to continuous time accounting data. (Merton 1990)

Supply chain management decision-making can experience qualitative changes from technology acceleration too. Take computer business. Computer manufacturers Dell and Gateway use internal models based on technology acceleration that completely depreciate inventory over a three-month period – implying 1% per day. Microsoft expenses all software development costs in the period they are incurred.

To conclude, understanding the impacts of accelerating technology to supply chain management, outsourcing strategies and R&D planning are crucial for success of firms in the 21st century.

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