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Abstract

The complex relationships between information technology investments and business value have been the focus of intensive research in recent years. There appears to be a discernible trend toward a more nuanced view in which the differential effects of the various categories of IT capital such as hardware, software, and their interactions with organizational factors are systematically investigated. As well, there is emerging evidence of accelerating investments in software and a greater shift toward "softwarization" (Langdon 2003) in which value addition is linked to combining flexible software with increasingly commoditized hardware.

In this paper, we focus on the differential contributions of hardware and software capital and their interactions with labor capital. We use industry-level data to extend previous studies in three ways: (1) by using more recent data (1990 to 2002), (2) by focusing on IT-using industries in the private sector, and (3) by treating IT hardware and IT software as two distinct classes of IT capital. We adopt the commonly used log-linear Cobb Douglas production function approach. Our findings indicate that the impacts of software are significantly different in comparison with hardware and that the productivity benefits attributable to IT are largely due to the interactions between software and labor inputs. We conclude that software is the key to productivity growth in the IT-using world, and show that it can be used as the closest surrogate to represent business complementarities to IT in macro-level studies.

Keywords: Productivity paradox, business value, IT investment

Introduction and Motivation

The original formulation of the productivity paradox[1] in 1987 initiated a line of research which treats information technology capital differently from other types of input capital in a production system. By 2003, Carr, in his controversial *Harvard Business Review* article, suggested that IT has evolved to a stage of a "commodity" with little strategic value to be derived from IT investments. His analogical argument is based on comparing IT evolution to the development of railways in the 1800s and electric power in the early 1990s. This controversial position has revitalised the debate surrounding IT investments and business value. In response to Carr, it has been suggested that extracting value from IT investments requires innovations in business practices which calls for complementary investments in software and its adaptation to organizational contexts. The capability of software to enable computers to achieve unlimited variability in features and functions has been highlighted by Strassman (2003). Brown and Hagel (2003) claim that IT continues to evolve and that the gap between IT potential and business realization of that potential

[1]Solow (1987) argued that, "You can see the computer age everywhere but in the productivity statistics."

has actually widened in recent years. As well, computers are no longer a full representation of IT equipment; OECD (2002) redefined IT to include various other components such as software, communications, and IT services in addition to computer hardware. This new definition captures the essence of general purpose technologies that have the potential to adapt and evolve (Bresnahan and Trajtenberg 1995) in different business environments.

We can see a phenomenal shift in emphasis from computer hardware to software in recent years both in IT-production activities (Anselmo and Ledgard 2003) and IT-use activities (Aley 2002; Kanakamedala et al. 2003). Langdon (2003) argued that value-added is being shifted from mechanical systems and their operations into software. He named this shift as "softwarization" and concluded that powerful hardware combined with flexible software will continue to fuel a process in which value addition is increasingly achieved with IT.

Another well-known issue has been the difficulties associated with measuring software impacts in the production economics approach. Software quality improvements are more subtle and harder to quantify than hardware (Brynjolfsson and Kemerer 1996; Greenspan 2000; Parker and Grimm 2000). As well, the economic impact of open source software (OSS) on business processes is still very much an open question. Weber (2000) described the problems of economic rents of OSS and argued that computing power is not the key survival necessity or value in the ecosystem because of its abundance and cheapness.

Recent studies (Bresnahan et al. 2002; Brynjolfsson et al. 2002) focusing on IT complementarities suggest that specific kinds of organizational adjustments (such as business process redesign) hold the key to increasing the impact of IT on business performance. Instead of investigating organizational factors as complementing the IT investments, we propose the alternative view that IT software may be one of the most important factors that needs to be subject to careful scrutiny. Implicit here is the notion of software as being continuously developed and adapted to accommodate the changing organizational needs.

In this paper, we report on one of the first attempts to systematically analyze the impact of IT software in conjunction with IT hardware on output at the industry level, drawing on the theory of production economics. We present the theoretical basis of our analytical approach in the next section. We then describe our research design and hypotheses. A description of the data is provided and the results are discussed using our model at the aggregate level, supplementing the analysis with insights from modified versions of the basic model. We also compare our findings with the results from previous related research. In conclusion, we evaluate our findings and suggest directions for further research.

Literature Review

There are many factors that may directly or indirectly influence the complex relationships between IT investments and business value (Brynjolfsson and Yang 1996; Chan 2000; Dedrick et al. 2002; Kohli and Devaraj 2003). Moulten (2000) concluded that the productivity paradox basically revolved around questions of measurement. In this section, we focus on the measurement problem in three ways: (1) the availability of properly defined input and output variables, (2) the estimation models used to represent the actual relationships between IT input and output variables, and (3) the level of analysis and control variables used.

Measurement of IT Components

The composition of IT capital has changed significantly since the Internet was introduced into the business processes in the mid-1990s. Romer (1995) argued that the computing metaphor replaces the traditional categories of inputs (capital, raw materials, production and non-production workers) with three broad classes of inputs: hardware, software, and wetware. Hardware includes all of the physical objects used in production (i.e., capital equipment, computers, structures, raw materials, infrastructure). Software includes all of the knowledge that has been codified and can be transmitted to others (i.e., literal computer code, blueprints, mechanical drawings, operating instructions for machines, scientific principles, folk wisdom, films, books, musical recordings, the routines followed in a firm, the literal figurative recipes we use, even the language we speak) where once the first copy of a piece of software has been produced, it can be reproduced, communicated, and used simultaneously by an arbitrarily large number of people. Wetware captures what economists call human capital and what philosophers and cognitive scientists sometimes refer to as tacit knowledge (i.e., all the things stored in the "wet" computer of a person's brain).

Langdon (2003) suggested two recent trends related to the unlimited potential of softwarization: (1) Moore's law, which establishes that hardware will become more powerful and cheaper over time, and (2) the advances in how increased processing power can be used, which leads us into the world of systems and software architecture design, with its fast-growing jungle of acronyms and ideas. Broadbent et al. (2003) conceded that although hardware, network connectivity, and even some standard commercial software packages may be commodity businesses, it is the intelligent and innovative software application of information that solves business problems and creates customer value. Louderback (2004) also concurred that exciting changes will come, not from basic Moore's law advancements in hardware, but from new software and concluded that the potential of more intelligent software will make the sea of information on our computers easier to manage than ever before.

It should be clear from the foregoing that IT can impact productivity in a variety of ways. Gurbaxani and Mendelson (1992) incorporated software in their empirical study because they believed that software (including both software development and maintenance) represents a growing proportion of information systems expenditures. Based on the premise that IT hardware and software potentially carry such divergent effects, there is a need to disaggregate IT capital into hardware and software capital in our estimation models. A similar attempt has been previously proposed by Rai et al. (1997) in which different types of IT investments were matched with an array of performance measures. They categorized IT input variables into five types of expenditure: client/server expenditure, IS staff expenditure, hardware expenditure, software expenditure, and telecom expenditure. This study pointed to the possible differential impacts of various IT inputs on a range of output measures. Gurbaxani et al. (1998) also treated IT hardware differently by disaggregating the IT hardware into three separate classes: mainframe computers, minicomputers, and microcomputers.

Availability of suitable data at the appropriate level of granularity has constrained research progress. Currently, not all developed countries manage to capture all IT components into their system of national accounts. While many countries are still trying to properly define IT services and communications equipment, a few are now able to separate their IT hardware and software investments from their ordinary capital stock (Colecchia and Schreyer 2001). An earlier study by Oliner and Sichel (1994) argued that computers represented only a small fraction of total capital stock and cannot make a large impact on aggregate productivity and went on to conclude that there is no missing productivity. Melville et al (2004) pointed out that software is often treated implicitly via assumptive measures or sometimes omitted entirely from the analysis. We conclude that earlier studies using solely computer capital (Brynjolfsson and Hitt 1996) can no longer be viewed as adequate to represent the complex relationships between the disaggregated IT inputs and productivity growth. As well, the recent inclusion of software investments by some of the national statistical agencies opens up the opportunity to deepen our understanding of this complex issue.

Estimation Methods

Although the production-function approach has been widely accepted (Alpar and Kim 1990, 1991; Brynjolfsson and Hitt 1996; Lichtenberg 1995) to test if computer equipment is positively contributing to output, a number of adjustments have been made to the traditional neoclassical production approach to test if (1) the computer is used as a substitute for or to complement other capitalized inputs such as labor (ESA 1998; Lichtenberg 1995), and (2) the enabling effects of IT by focusing on the factors external to the traditional input variables used in production economics (Bresnahan et al. 2002; Brynjolfsson et al. 2002).

The primary benefit of using the production function approach is that it provides a mathematical representation of a production process that relates the levels of inputs (i.e., IT, non-IT, and labour) in a firm, industry or economy to its output. Brynjolfsson and Hitt (1996) and Hitt and Brynjolfsson (1994) found that the marginal product of IT capital is significantly higher than non-IT capital. Based on estimates from several production functions, Byrnjolfsson and Hitt (1996) concluded that the IT productivity paradox seemed to have virtually disappeared by 1991. Other studies by Dewan and Min (1997), Kudyba and Diwan (2002), and Lichtenberg (1995) have confirmed the increasingly significant contribution of IT capital to firm-level outputs using more recent data. Coincidently, the investment in software has increased dramatically, reaching more than one-third of the total IT investments in the past 10 years (Ahmad et al. 2004). Our central argument is that the recent studies reviewed in the foregoing have contributed to a more positive picture of the critical role of larger software investments in producing increased business value.

Levels of Analysis

There have been concerns about the differential IT productivity impacts at various levels of analysis. Plice and Kraemer (2001) investigated the payoffs from IT investments at the international level by analyzing 6 years of output, employment, and investment data for 6 industry sectors in 36 countries. They found that the positive relationship between IT investments and productivity growth was only significant for developed counties, but not for developing countries, even though a significant positive relationship was found when the full set of countries was used. Others, like the McKinsey Global Institute (2001), found that only 6 out of 59 industries have significant positive correlation between IT investments and productivity. Brynjolfsson and Hitt (1996) incorporated the industry and time effects into their production function estimation and Stiroh (2001) and Van der Weil (2001) divided their dataset into IT-intensive and non-IT intensive industries to test for further benefits generated by IT capital. Removal of potential bias that affects the positive relationships between IT capital and productivity is important. For example, Brynjolfsson et al. (2002) incorporated fixed and random effects treatments to remove bias from time and industry factors. They also introduced additional independent variables into their regression estimation in an attempt to ameliorate some of the measurement problems caused by omitted variables.

Research Design and Hypothesis

We use the common log-linear production function to test the relationship between the level of output and the levels of various inputs, including IT-related and non-IT-related capital and labor. This simple technique has significant practical advantages: (1) data on quantities of inputs and outputs (in constant dollars terms) are more readily available and less controversial than the price estimates needed to construct meaningful cost function, and (2) by expressing the model in log-linear form, the coefficients of the explanatory variables are also the elasticities with respect to output. We can then use these elasticities to determine the marginal product.

This model was earlier used to test the hypothesis that the marginal product (the additional output the firm can expect if it employs one additional unit of specific input) of IT capital is larger than those of non-IT capital. Brynjolfsson (1993) and Lichtenberg (1995) extended the model to also test the hypothesis that marginal products of IT labor are larger than those of non-IT labor. More recently, Kudyba and Diwan (2002) used the same method and reported increasing returns to IT. This study compared the coefficients between different periods and concluded that the coefficients of the IT capital are higher in the later 1990s compared to the coefficients estimated in the earlier periods.

Software is increasingly the primary driver for providing new functionalities to store, retrieve, and distribute knowledge derived from large volumes of data, to rationalize and streamline business processes, and to facilitate the development of the extended digital enterprise. Our main focus of this study is to examine how much of the recent output growth and productivity gain can be attributed to software investment. In order to highlight the differences between the IT hardware and software, we examine data at the industry level in two stages.

Stage 1

In this study, for comparisons of net benefit from a particular input type, we assume that IT cost is similar across all industries. As the starting point of our analysis, we estimate a standard Cobb-Douglas production in log-linear form, similar to the one used by Brynjolfsson (1993). The general form of this function is

$$\ln Y = \alpha + \gamma IND + \beta_0 \ln K_0 + \beta_1 \ln K_1 + \beta_2 \ln L \tag{1}$$

where Y represents value-added of a specific industry in a single year; IND represents the possible industry effects; K_0 stands for non-IT capital stock; and K_1 stands for IT capital stock; L is labor hours worked. We estimate equation (1) essentially with pooled time series and cross-section data for 12 Australian industries (more on the data later) in the private sector over 13 years (1990 to 2002). Using Australian data has the advantage that it is a developed country like the United States but with a very small IT-producing industry. This dataset is particularly useful in studying the IT effects on a predominantly IT-using economy. We estimate the base production function (i.e., equation 1) using the entire data set by pooling all of the 156 observations. The base hypotheses tested for the contribution of IT capital are

> *Hypothesis 1a (H1a): IT capital (i.e., the combined investments of IT hardware and IT software) contributes positively to industry level value-added.*
>
> *Hypothesis 1b (H1b): The marginal product of IT capital is at least as high as its rental price*[2]

[2]The rental price is generally only a fraction of a capital asset since it is based primarily on interest, depreciation, and possible capital gain or loss. Rental prices are also referred to as users costs. For example, if we assume that IT equipment has an average asset life of 4 years (25 percent per year if a straight-line depreciation approach is used), any estimate of marginal product that exceeds the value of the rental price implies that its net benefit is positive.

Stage 2

We proceed to extend the base production function to equation (2) and equation (3) by estimating IT hardware and IT software independently and introducing interaction terms to test for associations between the two categories of IT capital, non-IT capital, and labor variables. The results from the additional specifications of the model provide useful analytical insights that enrich our understanding and interpretations of results.

$$\ln Y = \alpha + \gamma IND + \beta_0 \ln K_0 + \beta_{1h} \ln K_{1h} + \beta_{1s} \ln K_{1s} + \beta_2 \ln L \tag{2}$$

and

$$\begin{aligned} \ln Y = \alpha + \gamma IND + \beta_0 \ln K_0 + \beta_{1h} \ln K_{1h} + \beta_{1s} \ln K_{1s} + \beta_2 \ln L \\ + \beta_{1h2} \ln K_{1h} . \ln L + \beta_{1s2} \ln K_{1s} . \ln L + \beta_{02} \ln K_0 . \ln L \end{aligned} \tag{3}$$

where K_{1h} stands for IT hardware capital and K_{1s} stands for IT software capital in equations (2) and (3); $\ln K_{1h}.\ln L$, $\ln K_{1s}.\ln L$, and $\ln K_0.\ln L$ represent the interaction terms between IT hardware and labor, IT software and labor, and non-IT capital and labor respectively in equation (3). It should be noted that the labor input is not separated into IT and non-IT labor[3] due to the limitation of the dataset. Given our focus on the IT-using economy, it is probably more relevant to examine the interaction of IT with labor in general and not just the IT component of labor. The limitation of the dataset does not affect our model and hypotheses formulation. The hypotheses to test for the contribution of IT hardware and software and the interactions between each class of IT capital to labor input are

Hypothesis 2a (H2a): IT hardware independently contributes positively to industry level value-added.

Hypothesis 2b (H2b): IT software independently contributes positively to industry level value-added.

Hypothesis 2c (H2c): The marginal product of IT software is much higher than other types of capital (including IT hardware).

Hypothesis 3a (H3a): The interaction between IT hardware and labor contributes positively to industry level value-added.

Hypothesis 3b (H3b): The interaction between IT software and labor contributes positively to industry level value-added.

Hypothesis 3c (H3c): The interaction between non-IT capital and labor contributes positively to industry level value-added.

Data

We assembled annual time-series data from the National Accounts Division of the Australian Bureau of Statistics (ABS) for the period from 1990 to 2002 for 12 industries covering the full spectrum of the Australian market sector. Industry estimates of value-added and data on productive capital stock, both expressed in constant 2000 dollars at 1-digit ANZSIC level. Traditionally, productivity analyses have proceeded on the assumption that capital assets deliver economic services in proportion to the size of the installed capital stock (i.e., net of depreciation). Because different types of capital deteriorate at different rates unrelated to wealth depreciation, ABS provided us the volume of capital adjusted for efficiency losses according to the relevant ago-efficiency, defined as the productive capital stock of each asset over time.

The definitions we use in this study for IT capital and non-IT capital are based on the Australian Productivity Commission's research (Parham et al. 2001) in which IT capital consists of only two types: (1) computers under the category of "Other machin-

[3]The Australian Bureau of Statistics is unable to provide separate classes of labor inputs.

Table 1. Data Description of Australian National Accounts at 1-Digit ANZSIC Level between 1990 and 2002

Variables	Computation	Annual Average per Industry
Value-added (Y)	Gross value-added at 1-digit ANZSIC level deflated by Value-added index	$49.9 billion (100%)
Hardware Capital (K_{1h})	Computer and computer peripheral deflated by computer hardware price index	$1.3 billion (2.6%)
Software Capital (K_{1s})	Software capital deflated by computer software price index	$1.5 billion (3.0%)
IT Capital (K_1)	Sum of K_{1h} and K_{1s}	$2.8 billion (5.6%)
Non-IT Capital (K_0)	Sum of all other capital services measure in the market sector* deflated by non-IT capital index	$19.8 billion (39.7%)
Labor (L)	Labor hours-worked at 1-digit ANZSIC level	
Industry (IND)**	0 for service-oriented industries† 1 for otherwise‡	

*They are buildings, other structures, transport equipment, other machinery equipment excluding K_1, land, inventories, livestock, mineral exploration and artistic originals.
**It has been pointed out that the structure of production in service industries is different from other industries such as manufacturing (Triplett and Bosworth 2000).
†They are electricity, gas, and water; wholesale trade; retail trade; accommodation, cafés and restaurant; finance and insurance; transport and storage; communications services; cultural and recreational services.
‡They are manufacturing; agriculture; mining; manufacturing and construction.

ery and equipment" and (2) software[4] (including pre-packaged, own-account, and customized). Because communication equipment is not separated from other machinery, it is included under the non-IT capital measure. Descriptions of the variables are provided in Table 1.

Empirical Findings

Prior to the implementation of the regression models, a number of standard diagnostics tests were performed to ensure our model specifications do not violate the assumptions of the linear regression model: (1) analyses of the standardized residual terms confirm the normality of residual and homogeneity of residual variances, and (2) the collinearity diagnostics show no evidence of multicollinearity in our base regression equation (1).[5] For equation (2), the multicollinearity diagnostics show that IT hardware and IT software have lower tolerance and higher variance inflation factor (VIF).[6] These values are still acceptable for this analysis. It also indicates that investment decisions in IT hardware and IT software are sometimes considered jointly.

Although the cross-section pooled model provides a reasonable average representation of the economy level production function, we also tested for the possible effects of industry and time differences on industry level value-added. The results suggested that there were no significant differences between years, but there are significant differences across some industries only. The regression results are presented in Table 2.

[4]ABS currently uses Statistics Canada (StatCan) deflator to adjust for software capital which declines by 6 percent per year. Further details can be found in ABS (2000). ABS is currently reevaluating the quality measures to adjust computer and software prices (Zarb 2001).

[5]For equation (1), tolerance (VIF) of $\ln K_0$, $\ln K_1$ and lnL are 0.977 (1.023), 0.816 (1.225), and 0.832 (1.202) respectively.

[6]For equation (2), tolerance (VIF) of $\ln K_0$, $\ln K_{1h}$, $\ln K_{1s}$, lnL are 0.884 (1.132), 0.208 (4.804), 0.216 (4.620), and 0.834 (1.119) respectively.

Table 2. Regressions Results: Coefficient Estimates and Implied Gross Rates of Return
(The Numbers in Parentheses Are Standard Errors)

	Average Products	Equation (1) Elasticities	Marginal Products for (1)	Equation (2) Elasticities	Marginal Products for (2)	Equation (3) Elasticities
$\ln K_o$	2.519	.239*** (.038)	0.602	.280*** (.037)	0.705	2.212*** (.263)
$\ln K_1$	17.878	.369*** (.027)	6.597			
$\ln K_{1h}$	38.161			.079** (.037)	3.015	-.177 (.277)
$\ln K_{1s}$	33.635			.275*** (.034)	9.250	-1.669*** (.326)
lnL		.191*** (.027)		.197*** (.025)		.688*** (.253)
$\ln K_{1h}*\ln L$						-.025 (.027)
$\ln K_{1s}*\ln L$						.179*** (.030)
$\ln K_0*\ln L$						-.185*** (.024)
Control				Industry		
R^2		.865		.883		.953
F		241.36***		226.80***		330.56***
N		156		156		156

Key: ***p < .01, **p < .05, *p < .10

Stage 1 Regression Results

Based on the production function specified as equation (1) and using pooled data, the estimated elasticities of output with respect to all inputs, including non-IT capital, IT capital, and labor are all statistically significant with values of 0.239, 0.369 and 0.191 respectively (see column 3 in Table 2).[7] Using the estimated output elasticities, we calculated the marginal products of the IT and non-IT capital inputs.[8] First, we computed the average product of each capital input,[9] and then multiplied the average products by their respective estimated elasticity to derive the economy-wide marginal product. The results are presented in column 4 of Table 2. Note that the calculated marginal products of IT and non-IT capital are estimates of the contribution for an additional unit of the input across all industries.

The results show that the estimated marginal product of IT capital and non-IT capital are 6.597 and 0.602 respectively. IT inputs have much higher marginal products than non-IT inputs. The estimated marginal product of IT capital is 6.597, which implies

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[7]To test whether simultaneity exists between IT capital and output, we implemented a 2SLS model using lagged IT capital as the instrumental variable. The estimated elasticities of output with respect to all inputs, including non-IT capital, IT capital, and labor, were all statistically significant with values of 0.257, 0.370 and 0.187 respectively. These results are similar to our original model, suggesting our original model is robust.

[8]We expect the values of these coefficients to be positive but less than one, because they are elasticities which are the ratios of marginal products to average products. These ratios are expected to be less than one (i.e., marginal product to average product), because if marginal product were larger than average product, the firm would not be maximizing profits.

[9]Average product is the ratio of the total product of all industries to the total quantity of each input used by all industries.

that putting one additional dollar of IT capital stock into service for a year generates $6.597 of output. Since rental price cannot exceed 1,[10] our results show that the net benefit of IT investment is much higher than its rental price. Furthermore, the estimated marginal product of IT capital is nearly 11 times as large as that of non-IT capital (i.e., 6.597/0.602 = 10.98), thus suggesting that the rate of return to IT investment is much higher than non-IT capital.[11] We conclude that hypotheses (H1a), IT capital (sum of IT hardware and IT software) contributes positively to the industry-level value-added, and (H1b), the marginal products of IT capital is significantly higher than rental price (or usage cost), are both strongly supported.

Stage 2 Regression Results

An important feature of this study is the treatment of not just IT equipment as distinct from non-IT equipment but also treating IT software as distinct from IT hardware. As suggested earlier, it is important to examine whether there is statistical evidence to confirm the merits of this approach. We modified equation (1) by replacing IT capital stock with IT hardware and IT software capital stock. The extended production function is specified as equation (2). The coefficients of IT hardware and IT software can be tested for significance and also their marginal products can be compared to their rental prices separately. It should be noted that equation (3) has three additional interaction variables compared to equation (2). We employed a stepwise regression to estimate equation (3) so that the additional interaction variables were entered after the variables in equation (2) were estimated. The advantage of using this method is that the R^2 change could be tested for significance between the original regression equation (2) and the extended regression equation (3).

Software versus Hardware

The estimated elasticities of output with respect to all inputs, including non-IT capital, IT hardware, IT software, and labor were 0.280, 0.079, 0.275, and 0.197 respectively (see column 5 in Table 2). Most elasticities were positive and statistically significant at 0.01 level except IT hardware elasticity which, however, was statistically significant at 0.05 level. These results show that the elasticity for software alone is much higher than hardware (0.275 > 0.079) in equation (2) and also represents a large percentage of the IT capital in equation (1).

These regression results are very interesting when we compare them with the estimates using equation (1). First, the software elasticity captured most of the IT capital elasticity in equation (1) while the labor elasticities between the two equations remain roughly the same. Second, an improvement of R^2 from 0.865 to 0.883 was also observed, suggesting that the specification in equation (2) may have higher explanatory power than equation (1). Third, the estimated the marginal product of software not only was more than 3 times higher than the marginal product of hardware in equation (2) (9.250/3.015 = 3.068), but also roughly 13 times as large as that of non-IT capital (i.e., 9.025/0.705 = 12.8), which is also higher than the rate of return to IT capital calculated in equation (1). Fourth, the non-IT capital elasticity has increased from 0.239 to 0.280.

One explanation of such change in the coefficient of non-IT capital is that a part of IT hardware may have been wrongly labeled as a special type of capital like IT software. We test this speculation by combining IT hardware capital with the non-IT capital as one input measure (say ordinary capital) and treat IT software as the sole representative of the IT capital (say special capital) in the regression. The new estimated elasticities of output with respect to the industry control, ordinary capital (i.e., IT hardware + non-IT), special capital (i.e., IT software only), and labor are 0.466, 0.326, 0.319, and 0.212 respectively (where R^2 remains unchanged). All four elasticities are positive and statistically significant. These regression results show that inclusion of IT hardware improved the ordinary capital coefficient from 0.239 to 0.326, and the coefficient of special capital also improved from 0.275 to 0.319, thus suggesting IT hardware can be treated as another type of ordinary capital. We pursue this proposition with the specifications in equation (3). We conclude that all three hypotheses (H2a), IT hardware independently contributes positively to industry level value-added, (H2b), IT software independently contributes positively to industry level value-added, and (H2c), the marginal product of IT software is significantly higher than other types of capital (IT hardware and non-IT capital), are supported in our analysis.

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[10]The rental price for computer can be as high as 0.43 (Lehr and Lichtenberg 1999).

[11]The first order conditions for profit maximization require that the ratio of the marginal products of IT on non-IT capital be equal to the ratio of the user costs (i.e., rental prices) of capital for IT to non-IT. The ratio of the user cost of IT capital to other types of capital can be as high as 6 (Lau and Tokutsu 1992).

Time Trend and Lag Study

We first tested for the influence of time by adding a time trend variable in one case and lagged dependent variable in another. The result of regression analysis with the additional time trend variable was not statistically significant. We estimated another regression model using a modification of equation (2) that included the lagged dependent variable as an additional explanatory variable. This formulation considered rigidity in adjustment (the partial adjustment hypothesis, i.e., the possible difference between short-run and long-run equilibrium).[12] The estimated coefficient of the lagged dependent variable was statistically significant.

Among all the input variables in the regression equation, the only non-IT capital and IT software elasticities were found significant in the short-run. We conclude that IT software seems to produce short-term impact on the industry-level output, but not IT hardware. Our results support the tentative conclusion that the productivity gains due to software investments can be realized quicker than IT hardware.

Brynjolfsson and Hitt (2003) conducted a detailed analysis of productivity growth and found that, as longer time periods were considered, the relationship between computer investment and productivity became stronger. However, when we applied a similar method to our regression, we found contrasting results. Table 3 reports the production estimates with the two classes of IT capital and labor lagged up to four periods.

Table 3. Lagged Regression: Current Value-Added on Past Capital and Labor Inputs
(The numbers in parentheses are standard errors.)

Independent Variables	Dependent Variables				
	t	**t+1**	**t+2**	**t+3**	**t+4**
lnK_o	.280*** (.037)	.269*** (.038)	.257*** (.039)	.248*** (.039)	.243*** (.038)
lnK_{1h}	.079** (.037)	.076** (.038)	.074* (.038)	.054 (.041)	.006 (.043)
lnK_{1s}	.275*** (.034)	.288*** (.035)	.300*** (.036)	.326*** (.038)	.377*** (.040)
lnL	.197*** (.025)	.186*** (.026)	.177*** (.027)	.178*** (.027)	.185*** (.028)
Control			Industry		
R^2	.883	.887	.890	.897	.904
F	226.800***	215.917***	203.485***	198.152***	191.394***
N	156	144	132	120	108

***p < .01; **p < .05; *p < .10

[12]We estimate the adjustment coefficient (the fraction of adjustment completed with the current period) by subtracting the estimated coefficient of the lagged dependent variable from one. The value of zero for the estimated coefficient of the lagged dependent variable (i.e., that the adjustment coefficient is one) implies that the adjustment process is completely within the current time period.

These regression models can be interpreted as identifying the relationship between current output and past investments with various types of capital. Column 2 of Table 3 presents the results of the regression analysis that included the input variables in the current period (the same as column 5 of Table 2). We find that both non-IT capital and IT hardware elasticities decreased their impact on output over time. This result suggests that IT hardware behaves in a similar manner to non-IT capital in that their coefficients moved in the same direction over time. In contrast, the strength of the relationship between IT software and output grew over time as we consider its effects on output further into the future. These results clearly suggest that IT hardware and software behave significantly differently over time. It is, therefore, prudent to separate these two classes of IT capital in the estimation model. Furthermore, IT hardware loses its statistical significance in three years, thus suggesting that IT hardware loses its value at a quicker rate than non-IT capital.

Interactions between Non-IT Capital and Two Classes of IT Capital and Labor

Finally, we examined the interactions between non-IT capital and the two classes of IT capital stock and labor by incorporating three additional cross product terms in equation (2): the product of logarithmic values of IT hardware and labor, the product of logarithmic values of IT software and labor, and the product of logarithmic values of non-IT capital and labor.

We employed a stepwise regression such that all the independent variables in equation (2) are first entered and followed by the three additional interaction variables. This method provided an effective way to compare the impact of the interaction variables to the base regression equation. Note that a significant positive coefficient for the interaction between either categories of IT capital and labor would suggest that they are complements, while a significant negative sign would suggest that they are substitutes.

The estimated elasticities of output with respect to all inputs, including industry dummy, non-IT capital, IT hardware, IT software, labor, interactions between IT hardware and labor, interactions between IT software and labor, and interactions between non-IT capital and labor were 0.472, 2.212, -0.177, -1.669, 0.688, 0.025, 0.179, and -0.185 respectively (see column 7 in Table 2). Out of eight estimated coefficients, only IT hardware and the interaction term between hardware and labor turned out to be statistically insignificant. In order to understand the interaction, we need to consider each set of corresponding coefficients together rather than studying each estimate independently.

First, the significant negative coefficient of the term representing the interaction between non-IT capital and labor indicates that non-IT capital and labor are substitutes. Given that the individual coefficients of non-IT capital and labor are positive and significant (2.212 and 0.688 respectively), these values suggest that both inputs have a positive impact on productivity individually and are inter-substitutable.

Second, the coefficient of the term representing the interaction between IT software and labor is significantly positive. This positive coefficient indicates that IT software and labor are complements. Furthermore, while the coefficient of the interaction between software and labor is statistically significant, the coefficients of IT software dropped from 0.275 to -1.669. This drop suggests that some of the observed values of software are serving as proxy when such an interaction term is omitted from the regression equation. Our observation is consistent with the standard omitted-variables arguments. Greene (2000) argues that additional independent variables in the regression equation will alter the estimates of the value of the other input variables in a systematic way depending on the correlation of the observed input variables. These results suggest that investments on IT software independently may contribute negatively to the output.

Third, the coefficient of the terms representing the interaction between IT hardware and labor and the coefficient that representing IT hardware alone are both contributing insignificantly to output. These results confirm that IT hardware is different from IT software. We also test for the significance of the R^2 change between equation (2) and equation (3), the R^2 is increased significantly from 0.883 to 0.953, and note that equation (3) has a significantly greater explanatory power than equation (2).

We conclude that the hypothesis (H3a), the interaction between IT hardware and labor contributes positively to industry level value-added, is not supported; (H3b), the interaction between IT software and labor contributes positively to industry level value-added, is supported, implying that IT software and labor are complements; and (H3c), the interaction between non-IT capital and labor contributes positively to industry level value-added, is not supported, suggesting that non-IT capital and labor are substitutes.

Discussion and Conclusions

Based on the results reported in this study, we argue that although hardware and software are closely intertwined, they are nonetheless distinct concepts. This paper aims to provide new empirical evidence to describe the current state of the IT productivity paradox at the macro-level. Our study provides preliminary evidence to show that IT hardware can be treated as ordinary capital input which is consistent with Carr's (2003) controversial argument suggesting the computer has become another type of commodity. We are also able to conclude that software is the key to business value and productivity growth in the IT-using world. We make a strong case against treating IT hardware and software as one aggregate measure because of the potential to confound our understanding of the productivity effects of various capital inputs.

This paper has proposed two extensions to the base model used by earlier studies to tease out the impacts of IT on productivity more precisely. We estimated the model for the aggregate economy by pooling 13 cross-sections for 12 Australian industries after establishing that the elasticities are invariant over 1990 to 2002. Based on the commonly used production function approach, we found that all economy-wide elasticities are positive and fall between zero and one, which is consistent with other earlier studies using U.S. data. This study extended the base production function estimation equation to explore the relationships between two classes of IT capital (i.e., hardware and software).

Our findings clearly suggest that software is the key source of at least the Australian productivity gain during the last decade. All regression estimates in this study show that IT hardware and software behave differently. IT capital was largely dominated by computer hardware capital in the earlier studies which reported that the relationship between IT and productivity was initially inconclusive. Subsequently, IT software measures began to be included in IT capital measures in the 1990s. By the combining the software and hardware into an aggregate measure of IT capital, the positive relationship began to emerge and at an increasing rate. However, our study has taken a different approach and has provided preliminary evidence to indicate that IT software and not hardware is the driving force behind output growth.

Recent studies (such as Bresnahan et al. 2002; Brynjolfsson et al. 2003) suggested that organizational investments (e.g., business process reengineering) are crucial to assist the realization of computer investments. Our findings provide an alternative perspective on the IT productivity paradox by suggesting that software investments in particular are crucial to assist the realization of complementary business investments.

Our findings show that the relationship between software investments and output grew stronger as longer time periods were considered. The positive coefficient estimated for the interaction between software and labor variables suggests that these inputs are complements. Our results strongly support the proposition that productivity improvement is related to the effective *use* of computer software (i.e., the interaction between software and labor). IT software has always been considered as the link between users and business logic. A good example of this is the implementation of enterprise software, such as ERP systems which attempt to mirror the logical process of the business system. Hitt et al. (2002) reported that companies that adopted ERP were better performers on nearly all measures of business performance. Additionally, incremental improvement in productivity can be realized by either organizational adjustments or the fine-tuning of software programs. Ours is one of the first papers to advance this perspective through systematic economic analysis.

Further Research

A number of natural extensions to this study are possible. First, we can test this model on industry-level datasets from other countries to see if a similar trend can be reproduced. Second, firm-level studies will be useful to provide deeper insights to help control for some of the problems caused by data aggregation. Third, we can further test for other classes of IT capital independently such as IT communication capital and IT services when such data becomes available. Finally, Gurbaxani (2003) argued that productivity gain may not be observable in the use of standard packaged software. It will be interesting to drill down and see how each class of software (i.e., prepackaged, own-account, customaries, and even open source) impacts productivity differently.

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