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2011

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A Direct Measure of Technical Change and Its Economic Implications

by

Salifou Issoufou

A dissertation submitted in partial satisfaction of the
requirements for the degree of
Doctor of Philosophy

in

Economics

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor David H. Romer, Chair
Professor Barry Eichengreen
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Professor James A. Wilcox

Fall 2011

A Direct Measure of Technical Change and Its Economic Implications

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Abstract

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Professor David H. Romer, Chair

Movements in total factor productivity (TFP) have strong economic implications. For example, improvements in TFP are conducive to long-run economic growth. Also, variations in TFP explain cross-country income differences and, to many real business cycle economists, TFP shocks account for a large fraction of aggregate fluctuations. Despite being important, TFP is a black-box, or “some sort of measure of our ignorance about the causes of economic growth” (Abramowitz 1956, 11). Most economists agree, however, that technological change is a major component of TFP.

To evaluate the effects of technological change on TFP, there is a need for a good indicator of technical change because conventional indicators, whether presented as indirect or direct measures of technology, have shortcomings. The most important of these shortcomings is their inability to measure true technical change.

In the essays that follow, I present a new and direct measure of technical change and evaluate its economic implications. The direct measure is derived from actual inventions, in information and communication technology (ICT), identified by engineers that are expert in the field of technology. The exact timing of when the inventions are widely adopted is determined using contemporaneous and ex-post narrative coverage of the identified innovations. This new indicator of technical change has one key advantage over existing indicators in that it consists of actual inventions chosen by technology experts.

Using the new indicator, I find that technological innovations have significant impacts on TFP, output, hours, investment and consumption. In addition, and using variation in ICT capital intensity at the sectoral level, I present evidence that industries that use ICT capital more intensively gain more, in terms of productivity, from technological innovations. This sectoral finding provides new evidence that advances in information technology are not limited to industries that produce information technology, contrary to the neoclassical

prediction.

Furthermore, narrative evidence suggests that the introduction of major inventions leads market participants to react positively in anticipation of future improvements in productivity. A formal test of whether the aggregate S&P 500 significantly responds to technology shocks shows that stock prices fall following technology shocks, a result consistent with the finding by Jovanovic and Hobijn (2001).

To Carmen Best, Farida Salifou and Sara Salifou

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Acknowledgments

I would like to thank my adviser, David Romer for his guidance and support during my five years at Berkeley. I learnt the basics of graduate level macroeconomics from his first year course and since then he has been an ideal mentor to me. He always encouraged my ideas and pointed me to new directions whenever I encountered stumbling blocks in my research. I would also like to express my gratitude to my thesis committee members Professor Yuriy Gorodnichenko, Professor Barry Eichengreen and Professor James Wilcox for providing invaluable comments and suggestions. Their feedback played an important role in the development and final composition of the thesis.

I would like to thank Professor Christina Romer and Professor Pierre-Olivier Gourinchas in the department of economics, and numerous economists at the Federal Reserve Bank of San Francisco and at the International Monetary Fund for serving as a sounding board for many of my ideas. I thank fellow graduate students Lorenz Kueng, Evgeny Yakovlev and Urmila Chatterjee for many stimulating discussions. I also thank my friends Lorenz Kueng, Evgeny Yakovlev, Pedro Castro, Abdoulaye Yansane, Valerie Muravitzky, Mike Nealy and many others for making my stay in Berkeley a pleasant and memorable experience.

I would like to thank my parents and siblings and my ex-family-in-law for their constant love and encouragement. They have always supported me unconditionally in my endeavors.

My ex-wife Carmen Best has been a pillar of support during this whole undertaking. I thank her for her unlimited patience and understanding. Her cheerful attitude drove away my anxieties during the ups and downs of graduate student life. Finally, a special thanks to my daughters Farida and Sara, they are the cylinder head of the engine that drove me to the completion of this dissertation.

Chapter 1

Introduction

These revolutions periodically reshape the existing structure of industry by introducing new methods of production - the mechanized factory, the electrified factory, chemical synthesis and the like; new commodities, such as railroad service, motorcars, electrical appliances; new forms of organization. (Schumpeter, 1942, 68)

Understanding the nature and sources of shocks to Total Factor Productivity (TFP) is one of the most important goals in macroeconomics. One key reason is that shocks to TFP have important economic implications. Despite being important, TFP is a black box, or “some sort of measure of our ignorance about the causes of economic growth” (Abramovitz, 1956, 11). Most economists agree, however, that technological change is a major component of TFP.

To evaluate the effects of technological change on TFP, and hence its broader economic impacts, there is a need for a good indicator of technical change. In this thesis, I derive a direct measure of technical change from actual inventions in information and communication technology (ICT) - identified by engineers who are experts in their respective technology fields - and use that to quantify the behavior of key macroeconomic variables in response to technology shocks. The exact timing of when the inventions are widely adopted is determined using historical records. This new measure has one key advantage over existing indicators in that it consists of actual inventions identified by technology experts.

There is a large body of literature that studies technology shocks and their broad economic impacts. Before describing the main parts of this thesis, it is crucial to put this present work in perspective by first presenting a brief overview of the literature on technology shocks.

1.1 Macroeconomic Implications of Technology Shocks

The behavior of key macroeconomic variables in postwar United States is characterized by empirical regularities the most important of which include the procyclicality of TFP and

the broad-based co-movements between output, consumption, investment and hours worked in response to technology shocks. Existing body of theoretical and empirical knowledge attempting to explain the empirical regularities can be categorized in three dominant views each explaining the nature and importance of technology shocks in economic fluctuations: the real business cycle theory (RBC), the New Keynesian (NK) approach to business cycle, and the expectations-driven theory of fluctuations (EBC). It is useful to survey these different views before highlighting the main existing contributions to our understanding of the role of technology shocks.

1.1.1 The Views on Aggregate Fluctuations

With Kydland and Prescott (1982) and Long and Plosser (1983) as proponents, the RBC literature considers technology shocks as the major sources of macroeconomic fluctuations. This literature takes the schumpeterian argument that technology is driven by a stochastic process and nests that into the Ramsey model, extended to include labor - leisure choice, to analyze the behavior of key macroeconomic variables in response to technology shocks. The literature has received credit for the ability of its models to generate macroeconomic series that have statistical moments similar to those of actual aggregate series in postwar United States. Also, an important and celebrated prediction of these models is the simultaneous increase in output, investment and hours worked following a technological improvement. One major drawback of RBC models, however, is the high and frequent technology shocks (quarter to quarter) they require to explain observed aggregate fluctuations. It is arguably implausible to have an economy that is consistently subject to shifts its production function at high frequency level.

The NK approach to business cycle introduces nominal rigidities as well as technology, preferences, cost-push, and policy shocks in the traditional Keynesian models and evaluate the movements of key macroeconomic variables following each shock. A growing number of papers document the relative importance of non technology shocks to economic fluctuations. Examples of this line of work include Gali (1999) and Ireland (2004).

Gali questions a key prediction of the RBC literature, the negative correlation between productivity and hours worked, a finding that is inconsistent with actual data. He identifies and estimates the components of productivity and labor input variations associated with technology and non technology shocks by using structural vector autoregression (SVAR) and by imposing the identifying restriction that only technology shocks can permanently affect productivity. Gali's findings run counter to the predictions of the RBC literature but are consistent with NK models of nominal rigidity, monopolistic competition and variable labor effort. Two of his findings stand out. The first is the negative conditional correlation between productivity and hours following a technology shock and the second is the relative importance of non technology shocks in explaining the bulk of observed aggregate fluctuations in postwar United States. Similarly, Ireland (2004) presents empirical evidence that monetary policy shocks accounted for forty percent of variations in output growth fluctuation, almost twice

as much as the share attributed to technology shocks (25%).

The second alternative to RBC literature is the EBC approach. This literature argues that the economy can go through cycles of booms and busts with or without actual changes in fundamentals. For example, if economic agents receive signals about future changes in aggregate productivity, the euphoria (or pessimism) that ensues can lead to economic expansions (or contractions) regardless of whether actual fundamentals have changed. In this spirit, if there are some news or signals that aggregate productivity will improve in the near future, consumers and investors could increase their spending which will raise aggregate demand and contemporaneously expand aggregate activity. And if the actual change in productivity turns out to be less than what these consumers and investors expected, aggregate activity could contract without actual changes in fundamentals. The proponents of this theory include Beaudry and Portier (2006) and Jaimovich and Rebello (2008) and they argue that aggregate fluctuations can occur without any significant change in economic fundamentals. The premises of EBC date back to Pigou's (1927) *Industrial Fluctuations* wherein he attributes business fluctuations to real as well as psychological causes. The psychological causes relate to market participants' errors in forecasting future economic conditions and Pigou stressed the importance of these psychological causes which can produce fluctuations larger than what actual changes in economic conditions can accomplish.

The revival of the EBC comes in response to the inability of traditional neoclassical models to produce positive responses of output, hours, and investment following good news about future changes in productivity. Indeed, in standard neoclassical models, favorable news about future productivity produce recessions rather than expansions. These positive news about future productivity are followed by a decline in employment, output and investment, and an increase in consumption, as households, in response to an increase in expected wealth, raise their consumption of goods and leisure. To provide theoretical remedies, Jaimovich and Rebello (2008) introduce variable capital utilization rate, adjustment costs to investment, and preferences that produce smaller wealth effect on the labor supply into the neoclassical growth model. With these additions, Jaimovich and Rebello are able to generate, without actual technology shocks, a rise in output, investment, hours worked, and consumption following a good news about future changes in productivity. Beaudry and Portier (2006) present empirical evidence that favorable news about future change in productivity induce contemporaneous rises in output, consumption, investment and hours. More specifically, they use information contained in stock price that is contemporaneously uncorrelated with TFP but that affect TFP with a delay, as a measure of news about future changes in productivity. Shocks to this measure lead to a positive response of total factor productivity (TFP) not on impact but with a delay Beaudry and Portier (2006).

The different approaches to understanding the macroeconomic importance of technology shocks and shocks to agents' expectations about future changes in aggregate technology are far from satisfactory. Many issues can be raised regarding each of the three dominant views of aggregate fluctuations. First, the fact that the importance of technology shocks in accounting for aggregate fluctuations in postwar United States depends on whether one uses RBC or NK

framework does not tell us much about how changes to an economy's production function operates and where the changes are coming from. Second, the theoretical counterpart of measured technology is TFP which is the standard Solow residual. Variations in this measure, which are taken as measuring technological progress, are far from measuring true technical change since many factors other than technological innovations can affect TFP. A rise in output can stem from increasing return to scale, increase in intensity of capital and labor utilization and reallocation of inputs toward more productive firms. Third, even though it is plausible that shocks about future changes in productivity can have relevant macroeconomic effects, the existing literature does not explain what exactly constitute these shocks.

The following subsection presents a summary the main literature on the identification of actual technology shocks and their broad economic implications.

1.1.2 Actual Technology Shocks and their Implications

The main contributions of this thesis - identification of actual technology shocks and their implications are related to three existing work that have looked at alternative measures of aggregate technology: Shea (1998), Basu et al. (2006), Alexopoulos (2010), and Alexopoulos and Cohen (2009).

Shea addresses the role of technology in business cycles by investigating the dynamic interaction of inputs, TFP, and two measures of technology: research and development spending (R&D) and the number of patent application (both at annual frequency). Using vector autoregressions (VAR), Shea shows that favorable shocks to his measures of technology increase input use in the short run but reduce it in the long run. Shea also finds that shocks to R&D and patent applications do not increase TFP at any horizon and only explain a small fraction of input and TFP volatility at business cycles frequency.

In an effort to shed light on the behavior of macroeconomic variables following technology shocks, Basu and co-authors construct a purified measure of technology. Based on the known flaws of standard TFP to accurately measure technological progress, Basu et al. construct their measure of purified TFP by controlling for non technology effects in aggregate TFP. These include varying rate of capital and labor utilization, non constant return to scale, imperfect competition and aggregation effects. They find that a technology improvement is contractionary in the sense that inputs and investment fall in the short run. In their results, output does not change on impact but increases after a few years when inputs and nonresidential investment recover Basu et al. (2006).

Alexopoulos (2006) and Alexopoulos and Cohen (2009) construct indicators of technological change using the number of book titles published in the field of technology. With this measure, they find results consistent with the RBC prediction which means that following a technology improvement, employment, TFP, capital and output all increase.

These studies by Shea (1998), Basu et al. (2006), Alexopoulos (2010), and Alexopoulos and Cohen (2009) have their merits but they also have shortcomings. We do not know which technological innovations have actually affected aggregate economy during postwar United

States. Also, the use of purified measures of TFP does not tell us the nature and sources of technical progress. As for patents and R&D, there are a few issues associated with each of the two. There is a time lag between when a patent is applied for and when the product from that patent actually hit the market for commercial use. In addition, changes in patent applications can arise as a result of changes in laws governing the patenting process and very few patents are associated with actual product commercialization. As for R&D spending, they will not capture actual technological progress because today's spending will not be associated with today's inventions. Finally, book titles in the field of technology do not disentangle true from irrelevant innovations. For example, in any given year, the number of book titles in the field of technology can rise or fall without any associated contemporaneous technical change. It is therefore useful to look for different indicators of technical change.

1.2 Overview of the Thesis

This thesis contributes to the existing body of knowledge in two ways. First, a new and direct measure of technology shocks is derived using an approach that has not been applied to the identification of these types of shocks before. Second, this new measure is used to present new evidence on the macroeconomic implications of technical change. By identifying technology shocks directly, this thesis addresses one of the shortcomings of the alternative measures of technology suggested by Shea (1999), Basu et al. (2006), Alexopoulos (2006) and Alexopoulos and Cohen (2009).

The two main contributions of this thesis are organized in three chapters. Chapter 2 discusses the methodology used to identify technology shocks in postwar United States. I use a study by the National Academy of Engineering to isolate the inventions and I complement that with reading of historical records to determine the dates when the inventions were successfully commercialized. The use of historical records to identify macroeconomic shocks is pioneered by Friedman and Schwartz (1963) and refined in Romer and Romer (1989; 2004a; 2004b). Similar studies include Romer and Romer (2009; 2010), Ramey and Shapiro (1998) and Ramey (2008) for analyses of fiscal policy; and Hamilton (1985) for oil shocks.

Given the plethora of technological innovations in postwar United States, it is necessary to narrow the focus of the identification to specific types of technologies. In this thesis, the focus is on innovations in electronics and computing, or information and communications technologies (ICTs). The choice of ICTs is driven by the finding by Helpman and Trajtenberg (1996) and Mokyr (1990) that ICTs have the characteristics of general purpose technologies which have a high likelihood of being exogenous to aggregate activity. In addition, major technological breakthroughs take longer than one period to diffuse through the economy. Therefore, actual technology shocks are identified by looking in the narratives for evidence of when these breakthroughs were first implemented or commercialized.

In chapter 3, the behavior of key macroeconomic variables including output, TFP, labor productivity, hours, investment, consumption, and stock price are analyzed both at the

aggregate and sectoral level. One key question is whether there exist economically significant short and long run effects of identified technology shocks on real economic activity. Another key question is whether the identified technology shocks explain large fractions of observed aggregate fluctuations in postwar United States.

In the last chapter, a summary of markets reactions during the introduction of the isolated ICT inventions is first presented before exploring contemporaneous stock price responses. This chapter represents a first pass at a formal and informal evaluation of the predictions of the EBC theory. If the measures of stock prices are significantly affected by the direct measure of technical change, this would be evidence that stock prices respond to expectations about future improvements in TFP.

The rest of the thesis is structured as follows. Chapter 2 describes the methodology used to derive the measure of technical change. Chapter 3 describes the results of aggregate and sectoral implications of the new measure. Chapter 4 provides an overview of the market reactions to the introduction of major technological innovations before presenting the concluding remarks.

Chapter 2

Derivation of the Direct Measure

A central goal of this thesis is to look for technological innovations that one would expect to have an impact on economic activity and trace their effects on TFP and other macroeconomic variables. Because many innovations could fit this profile, it is necessary to adopt a systematic approach to successfully identify innovations that truly matter. In this chapter, I discuss the methodology used to isolate innovations that constitute the basis of the new indicator of technical change before .

2.1 Methodology

The methodology revolves around 4 key steps. In the first step, the focus is narrowed to a specific type of technology. The candidate chosen in this thesis is information and communication technologies, or ICT. This choice is partly driven by the fact that such technologies have general purpose characteristics. As Helpman and Trajtenberg (1996) and Mokyr (1990) argue, general purpose technologies (GPT) are pervasive and used in many sectors of the economy, they are subject to continuous technical change after introduction, their effective use requires complementary investment in the using sector, and they enhance productivity of R&D in the downstream sector. Such technologies have the potential to explain movements in TFP as well as having other economic implications.

The second step consists of limiting the focus to major ICT innovations only. In this thesis, major innovations are defined as new products, processes, or government legislation that experts in the field of technology identify as having had great economic and social impact. The use of this definition allows me to focus solely on innovations in information technology that were introduced in the postwar United States and which technology experts have chosen for their significant economic and social contributions.

The third step involves determining the timing of adoption or implementation of these innovations. This involves consulting official documents released by companies responsible for the inventions as well as documents written by technology experts that discuss the adoption

of such innovations. Reading these records allows for the derivation of a measure of technical change that takes into account the lags that exist between the introduction, or announcement, of an invention and its successful adoption or commercialization.

The fourth and last step consists of the derivation of the measure of technical change. This new measure is a time series that has for observations the number of major innovations adopted in a given year.

In isolating major innovations in information technology, I use a study conducted by the National Academy of Engineering (NAE). This study is used because its definition of what constitutes a major innovation matches the definition adopted in this thesis. Also, given that the NAE is a renowned body of experts, using inventions that they have chosen gives credibility to the direct measure of technical change. In the following section, I describe the NAE study and the major ICT innovations that were subsequently isolated based on the aforementioned constraints.

2.2 Major ICT Innovations

The NAE study is about 20th century engineering achievements. A consortium of 27 professional engineering societies worked to identify and communicate ways that 20th century engineering has affected our lives. With help from the American Association of Engineering Societies, the NAE used a congressional charter to convene the world's greatest engineering minds and coordinate the process of determining which of the 20th century innovations made great contributions to the standard of living.

The process of determining the greatest achievement is as follows. The NAE issued a call for nomination to the societies. To make the nominations, each engineering society polled its membership and learned about what engineers thought were the greatest achievements in their respective fields. The NAE then convened a selection committee of leading engineers from all fields to analyze the information contained in the nominations. After several rounds, the committee determined which engineering achievements of the 20th century had the greatest positive effect on human kind. The committee stated that the selected achievements are all equally important because if one of the innovations that the committee selected were to be removed, our world would be different. More specifically, they argue these innovations “are technologies that have become inextricable parts of the fabric of our lives - some spectacular, some nearly invisible, but all critically important” (Constable and Somerville, 2003, 6).

The committee determined twenty categories of engineering achievements: Electrification, Automobile, Airplane, Water Supply and Distribution, Electronics, Radio and Television, Agricultural Mechanization, Computers, Telephony, Air Conditioning and Refrigeration, Highways, Spacecraft, Internet, Imaging, Household Appliances, Health Technologies, Petroleum and Petrochemical Technologies, Laser and Fiber Optics, Nuclear Technologies, and High-performance Materials. From each achievement category, a timeline of critical

innovations was also determined. This thesis focuses on the three of these categories that were central to the ICT revolution: computers, electronics, and telephony.

The approach adopted here, despite its merits, has limitations. One key limitation of this approach is that the NAE study is geared toward isolating those innovations that are critical only in hindsight. Therefore, there is a potential built-in upward bias associated with this approach. Another limitation is that given that the ICT innovations isolated here are based on a study conducted in the late 1990s to early 2000s, and that was focused on the twentieth century innovations, there may be a tendency to ignore some innovations that were critically important but whose obvious effects were not observed by the engineers making the selection. This means that the impact of major ICT innovations may be underestimated due to the absence of some critical innovations introduced late in the century that could have had significant economic implications. Furthermore, this study only focuses on three fields of ICT and all the innovations have equal weights. These fields are electronics, computers, and telephony.¹

There are three key advantages of this approach, however. First, the innovations were chosen by experts in the fields of technology and the selection process was based on a survey of a wide range of renowned engineering professionals. This gives some credibility to the list of innovations. Second, by looking at only a few big innovations and the fact that these innovations are of the same type, I am only focusing on one of the many forms technical change might take. Third, it is crucial to accurately determine the dates of commercialization of the isolated ICT. This is because ICT have general purpose characteristics and one of the features of general purpose technologies is that their economic impacts may take a long time to materialize from the time of their introduction. There is a significant lag between when an innovation is introduced and when it successfully diffuses through the economy. Finding the accurate commercialization dates will make it more likely to obtain reliable estimates of the economic impacts of ICT shocks.

¹Note that Internet is one of the 20 fields identified by the NAE. It is reasonable to argue that the innovations from this category should be included in the measure of technology shocks. However, there are two reasons why Internet as a category is not included. First, prior to its commercialization, the Internet was only of limited use in that it was only available to a select few academic and government institutions. Second, the commercialization of the Internet, which occurred in 1991, is counted as one innovation by the NAE in the "computers" category.

2.3 Derivation of the Direct Measure of Technical Change

Figure 2.1: Number of major innovations introduced during the period of 1945-2000.

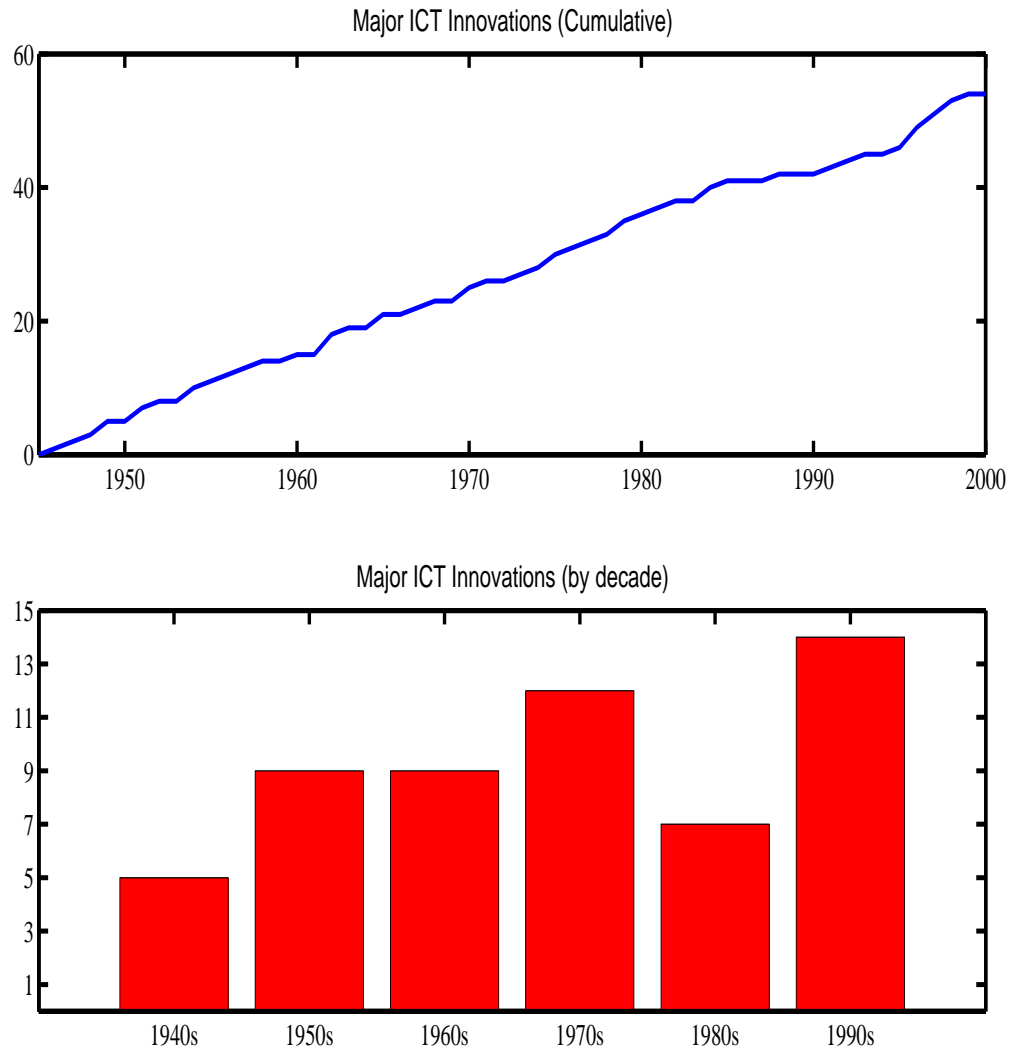


Figure (2.1) shows the frequency of major ICT innovations. Over the entire period, the average occurrence is one innovation per year. The 1990s have the highest number of introduced ICT innovations, followed by the 1970s. The 1940s register the lowest occurrence of ICT. The number of major ICT introduced fell from twelve to seven in the 1980s.

It is worth highlighting that most of the innovations are product innovations (forty out of fifty-four) and that government legislation pertaining to information and communication are among the fifty-four. The latter include the Telecommunications Act of 1996, the official approval of commercial cellular phone services in 1982, and the chartering of the Internet Corporation in 1998.

The NAE dates the inventions according to when the products or processes were brought to the market, which corresponds to their introduction year. My reading of the historical records show that fourteen of the fifty-four ICT innovations were widely adopted, or commercialized, a few years after their introduction.

Table (2.1) shows the list of the isolated innovations.

It is from this list of fifty-four major ICT innovations that I derive the new indicator of technical change. I combine the year of introduction provided by the NAE with the year of adoption determined using the historical records to derive the measure. This measure, therefore, consists of the number of innovations adopted or commercialized in a given year.

In the following chapter, the economic implications of the new indicator are examined. First, I investigate whether the new measure can explain movements in TFP and whether it has other economic implications at the aggregate level. Second, I evaluate whether sectors that use ICT more intensively benefit from the adoption of new inventions in ICT. Positive sectoral results would solidify any aggregate finding and would also provide new evidence in support of the theory of general purpose technology, which predicts that sectors that use ICT capital do see their TFP benefit from new inventions in ICT.

Table 2.1: List of Major ICT Innovations Identified by the NAE.

ICT Innovations	Category	Commercialization
ENIAC	Computers	1946
North American Numbering Plan	Telephone	1947
Point Contact Transistor	Electronics	1951
EDSAC	Computers	1949
Introduction of Model 500	Telephone	1949
UNIVAC	Computers	1951
First Long Distance Calls (NJ)	Telephone	1962
Computer Compiler	Computers	1952
Silicon Transistor	Electronics	1954
All Transistor Radio (Regency TR1)	Electronics	1954
Disk Drive (for RASD)	Computers	1956
Transatlantic Telephone Cable - TAT-1	Telephone	1956
Fortran	Computers	1957
Integrated Circuit	Electronics	1961
Compact PDP - 1	Computers	1960
MOSFET	Electronics	1962
Commercial Digital Transmission System	Telephone	1962
Telstar 1 Satellite	Telephone	1962
Introduction of the Touchtone Telephone	Telephone	1963
Electronic Central Office Switching System	Telephone	1965
Automatic Adaptive Equalizer	Electronics	1966
First Handheld Calculator	Electronics	1967
Computer Mouse	Computers	1984
Creation of PARC	Computers	1970
Digital-to-Optical System	Electronics	1970
Intel 4004 Microprocessor	Electronics	1971
Invention of the First Portable Phone	Telephone	1983
TMS 1000 (Original Introduction in 1972)	Electronics	1974
Altair 8800	Computers	1975
Fiber Optics	Telephone	1978
Common Channel Interoffice Signaling	Telephone	1976
Apple II	Computers	1977
First Public test of Com. Cell Phone	Telephone	1983
VisiCalc Spreadsheet	Computers	1979
First Laptop Computer	Computers	1982
BIST Technology	Electronics	1980
IBM Personal Computer	Computers	1981

Table 2.1: (continued)

ICT Innovations	Category	Commercialization
Com. Cell Phone Service Approved	Telephone	1983
Macintosh	Computers	1984
CD-ROM	Computers	1984
Windows 1.0	Computers	1985
Transatlantic Fiber Optic Cable	Telephone	1988
Internet Going Public (www Software)	Computers	1991
PDA	Computers	1993
Mosaic	Computers	1994
Commercial Internet Phone Software	Telephone	1995
Palm Pilot	Computers	1996
Telecommunication Act of 1996	Legislation	1996
TPC-5 All-Optic Fiber Cable (Pacific Ocean)	Telephone	1996
Fiber Optic Link Around the Globe (FLAG)	Telephone	1997
Copper-Based Chip Technology	Electronics	1998
Internet Corporation Chartered	Legislation	1998
Plastic Transistor	Electronics	2002
Palm VII	Computers	1999

Chapter 3

Aggregate and Sectoral Implications

Aggregate total factor productivity (TFP) is a crucial variable in macroeconomics. For example, improvements in TFP are associated with long-run economic growth. Variations in TFP help explain cross-country income differences. And, to many real business cycle economists, TFP shocks account for a large fraction of aggregate fluctuations. Despite being important, TFP is a black box, or “some sort of measure of our ignorance about the causes of economic growth” (Abramovitz, 1956, 11). Most economists agree, however, that technological change is a major component of TFP.

To evaluate the impacts of technological change on TFP, and hence its broader economic impacts, there is a need for a good indicator of technical change. In this chapter, I use the direct measure of technical change, derived in chapter I, to quantify the behavior of key macroeconomic variables in response to technical change. As indicated in chapter I, this new measure is derived from actual inventions in information and communication technology (ICT), identified by engineers, who are experts in their respective technology fields. The exact timing of when the inventions are widely adopted is determined using historical records. This new measure has one key advantage over existing indicators in that it consists of actual inventions identified by technology experts.

Using this new indicator, I find that the “measure of our ignorance,” TFP, is indeed impacted by the inventions identified by engineers. This means that major postwar inventions in information technology are good candidates to shed some light in the TFP black box. In addition to the effect on TFP, the new indicator has many other economic implications.

At the aggregate level, I find that ICT innovations have positive effects on TFP, output, hours, investment and consumption. The contemporaneous effect on TFP is zero, while that on hours and output is negative. This result is puzzling in that it differs from previous work. For example, from the real business cycle’s perspective, a positive technology shock raises both productivity and output along with labor input while in a sticky price model, a technological improvement leads to higher productivity, lower labor input and an unchanged level of output. Although it is hard to accurately estimate the contemporaneous response to a technology shock using low frequency data (annual data), one plausible explanation for

this puzzling result is that firms overestimate the importance of technical change and lower labor input by more than what is optimal. Another explanation is that technological change has to be embodied in new capital before it can affect output.

Using VAR produces similar macroeconomic dynamics and variance decomposition indicates that technology shocks do not explain a big share of macroeconomic fluctuations. Overall, the aggregate implications of technology shocks are that they have important and positive medium and long run effects but they do not account for a big share of aggregate fluctuations.

At the sectoral level, I use disaggregate industry data to investigate whether TFP is more responsive to ICT innovations in sectors that use ICT capital more intensively. This step is implemented for two reasons. First, it is crucial to ensure that the major ICT innovations, identified by engineers, are reliable. If these innovations are to have an effect, it should be more pronounced in sectors that use ICT capital more intensively. Second, using sectoral variation in ICT capital I can determine whether TFP growth in industries using ICT is affected by new inventions. According to the neoclassical growth theory, use of ICT leads to capital deepening, raising labor productivity but not TFP, in sectors that use but do not produce ICT. This prediction is different from the general purpose technology (GPT) theory Helpman and Trajtenberg (1996), which argues that ICT leads to TFP growth in sectors that use ICT. Therefore, if there are strong effects of ICT innovations in ICT-intensive sectors, this would be evidence that ICT innovations are important. It would also confirm the prediction of GPT theory.

I find that industries that use ICT capital more intensively benefit by more, in terms of TFP growth, from adopting the newly available ICT. This result not only corroborates the aggregate findings that ICT innovations are important in explaining TFP movements, but it also supports the prediction of the theory of general purpose technologies.¹

The approach taken in this chapter is related to three strands of literature.

The first strand looks at different measures of technology and evaluates their economic implications. This strand can be broadly divided in two main categories.

In the first category, indirect measures of technology are used to infer the effects of movements in TFP. Examples include growth accounting, Gali's (1999) use of long-run restrictions in a structural vector autoregressions, and Basu, Fernald and Kimball's (2006) use of purified measure of TFP.² These approaches have shortcomings in that they all constitute residual analysis. In addition, long-run restrictions require the assumption that only technol-

¹It is worth noting that this study is not the first to report results in support of GPT. Basu and Fernald (2007) present industry evidence that TFP acceleration is positively correlated with ICT capital. Although the approaches are different, the two studies reach similar results.

²Based on the known flaws of standard TFP to accurately measure technological progress, Basu et al. (2006) construct their measure of purified TFP by controlling for aggregation effects, nonconstant returns, varying utilization of capital and labor, and imperfect competition. They find that a technology improvement is contractionary in the sense that inputs and investment fall in the short run. In their results, output does not change on impact but increases after a few years when inputs and nonresidential investment recover.

ogy shocks affect TFP in the long-run, an assumption that does not align with endogenous growth theory.

In the second category, researchers attempt to alleviate the shortcomings that plague the indirect approach. As a result, they use direct measures of technical change to identify the impacts of technology shocks. Examples include Shea (1998) and Alexopoulos (2010). Shea (1998) addresses the role of technology in business cycles by investigating the dynamic interaction of inputs, TFP, and two direct measures of technology: research and development spending (R&D) and the number of patent applications (both at annual frequency). Using vector autoregressions, Shea shows that favorable shocks to his measures of technology raise input use in the short run but reduce it in the long run. Shea also finds that shocks to R&D and patent applications do not increase TFP at any horizon and only explain a small fraction of input and TFP volatility at business cycle frequencies. Alexopoulos (2010) constructs indicators of technological change using the number of book titles published in the field of technology. With this direct measure of technology, Alexopoulos finds results consistent with the RBC prediction. Indeed, in her paper, following a technology improvement, employment, TFP, capital and output all increase.

This chapter is closely related to Shea (1998) and Alexopoulos (2010) in that I also use a direct measure of technical change. There are important differences, however. The link between R&D spending, patents and actual technical change is not clear cut. For example, there are many lags between when the spending on R&D occurs and when the inventions that benefit the economy are adopted. Also, patents can change because of changes in patenting policies, which will weaken the relationship between the number of patents and actual technical change. As for the indicator based on books published in the field of technology, its shortcomings include the trends in publishing and the restrictions that some publishing houses impose on what to publish. This weakens the relationship between an indicator of technical change based on the number of books published in the field of technology and actual technical change. My new measure of technology has the advantage of capturing actual inventions, identified by experts in the field of technology, as they are being adopted throughout the economy.

The second strand relates to the ICT revolution and its productivity implications. The question of whether ICT leads to productivity gains was an important research topic even prior to the productivity acceleration of the 1990s. A comment made by Robert Solow, “You can see the computer age everywhere but in the productivity statistics” Solow (1987), arguably set the stage for the keen interest in the study of the relationship between ICT and productivity.³ This large literature includes Jorgenson and Stiroh (1999), Oliner and Sichel (2000) and Basu and Fernald (2007), among many others.

The present chapter differs from the literature on productivity resurgence in that those papers use growth accounting, with ICT capital as an input, to analyze the contributions of ICT to output and TFP growth. Also, the productivity resurgence papers put an emphasis

³For a review of the Solow paradox’s literature, see Triplett (1999).

on the late 1990s-early 2000s period and use post-1980 data. My thesis, and this chapter in particular, focuses on the role ICT inventions have played in the entire postwar period and I use impulse response functions to determine the responses of TFP, output and many other key macroeconomic variables following ICT innovations. Nevertheless, using a different method, this chapter's results are qualitatively similar to those in the Jorgenson and Stiroh (1999), Oliner and Sichel (2000), and Basu and Fernald (2007) to the extent that ICT innovations have important implications for TFP and output.

The rest of the chapter is structured as follows. In the following section, I evaluate the aggregate implications of the direct measure of technical change. Section 2 discusses sectoral implications of ICT innovations using variations in ICT capital intensity combined with the new indicator of technical change. In section 3, concluding remarks are briefly presented.

3.1 Aggregate Implications of the New Indicator

3.1.1 Specification

To formally test whether the new measure of technical change explains movements in aggregate TFP and other key macroeconomic variables, I use the following specification, which is a simple autoregressive distributed lag model.

$$x_t = \alpha + \sum_{i=1}^p \beta_i x_{t-i} + \sum_{i=0}^d \lambda_i z_{t-i} + \epsilon_t. \quad (3.1)$$

In this specification, x_t represents the growth rate of a given macroeconomic variable and z_t is the new measure of technical change. This measure of technical change is dated by commercialization. Therefore, the measure, as described in the previous section, has for observations the number of major ICT innovations identified by the NAE that are adopted in a given year. Also, and as noted above, the innovations are not weighted.

In equation (3.1), the inclusion of lagged values of each macroeconomic takes into account their normal dynamics. z_t and its lags are included to capture the direct effect of the measure of technology shocks on each macroeconomic variable. An implicit assumption in equation (3.1) is that z_t is exogenous. This is a reasonable assumption that is partly supported by historical records. Indeed, many of the identified ICT innovations were not brought to market as a result of a rise in macroeconomic activity. Nevertheless, one could include factors other than technical change that can affect x_t . In this regard, I extend equation (3.1) by including monetary, fiscal, and supply factors. This gives the following specification:

$$x_t = \alpha + \sum_{i=1}^p \beta_i x_{t-i} + \sum_{i=0}^d \lambda_i z_{t-i} + \sum_{k=1}^3 \Gamma_k C_t^k + \epsilon_t. \quad (3.2)$$

where $\sum_{k=1}^3 C^k$ corresponds to the growth rate of real federal government spending, the growth rate of M1, and the growth rate of oil price (crude).⁴

To obtain estimates of the effects of technical change, I find the implied impulse response functions.⁵ The advantage of using impulse functions is that one can see the dynamic relationship between TFP, for example, and technical change. In fact, tracing the response of TFP following a one-time realization of an ICT innovation informs us about how an innovation diffuses through the economy and approximately how long such diffusion takes.

3.1.2 Data

For the aggregate economy, I estimate the model using the following as dependent variables: aggregate "purified" total factor productivity (BFK TFP) from Basu et. al (2006), standard non-farm business sector total factor productivity (TFP)⁶, non-farm business sector labor productivity (LP - output per hour) from the Bureau of Labor Statistics (BLS), hours worked in the non-farm business sector (H) from the BLS, real GDP (Y) from the National Income and Products Account (NIPA), real private fixed investment (I), real consumption expenditures (C), real durable goods consumption expenditures (DG C), real non-durable goods consumption expenditures (NDG C), real services consumption expenditure (Sv C) and real investment in equipment and software (E&S I). The last six variables are from FRED database (Federal Reserve Bank of St. Louis).

3.1.3 Results

I estimate equations (3.1) and (3.2) for TFP, output, consumption, investment, hours worked and labor productivity using OLS to evaluate the impact of technical change. Equation (3.2) is an extension of equation (3.1) and controls for demand and supply factors that affect the macroeconomic variables of interest. For all the dependent variables, three autoregressive lags and six lags of the innovation variable are used in the estimation.⁷ All the estimations are based on annual data from 1949 to 2007.

⁴Note that the coefficients of z_t should not be affected by the inclusion of the demand and supply factors. If the coefficients change, then the assumption that z_t is uncorrelated with other factors affecting the macroeconomic variables would be problematic.

⁵The following dynamic multiplier is used to compute the impulse response functions of each variable following a one-time realization of an ICT innovation:

$$\left(I - \sum_{i=1}^p \beta_i L^i \right)^{-1} \sum_{i=0}^d \lambda_i L^i$$

⁶This version of TFP is constructed by the author using output, hours worked and capital services data from the BLS

⁷Note that using the coefficients from equation (3.1) and (3.2) produce similar impulse response functions.

Figure 3.1: Impulse response functions: Responses of aggregate variables following a one-time realization of ICT innovations. TFP and BFK TFP stand for total factor productivity and Basu, Fernald and Kimball (2006) measure of purified Solow residual, respectively. Dashed (red) lines represent 90 percent non-parametric bootstrapped confidence bounds and the numbers on the horizontal axis correspond to years after the shock. The results are based on annual data from 1949 to 2007.

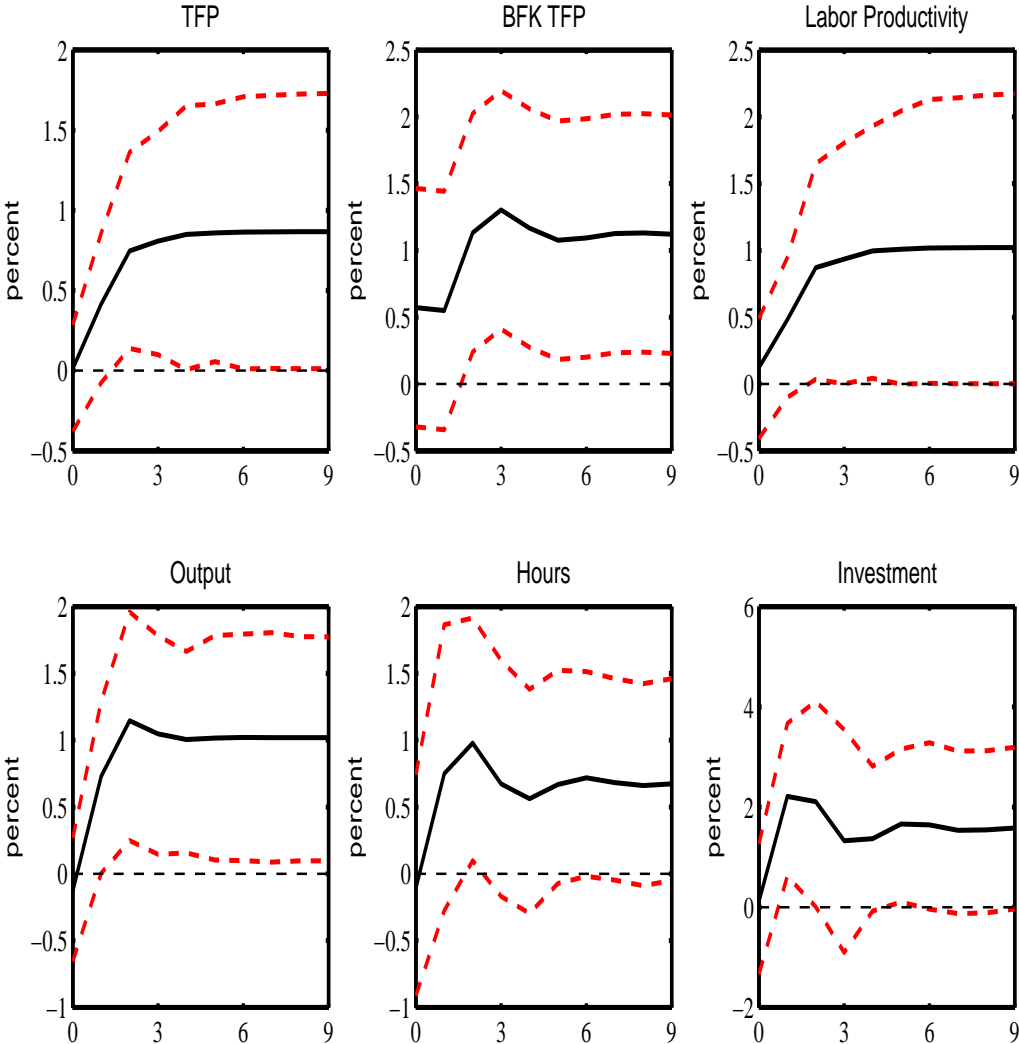
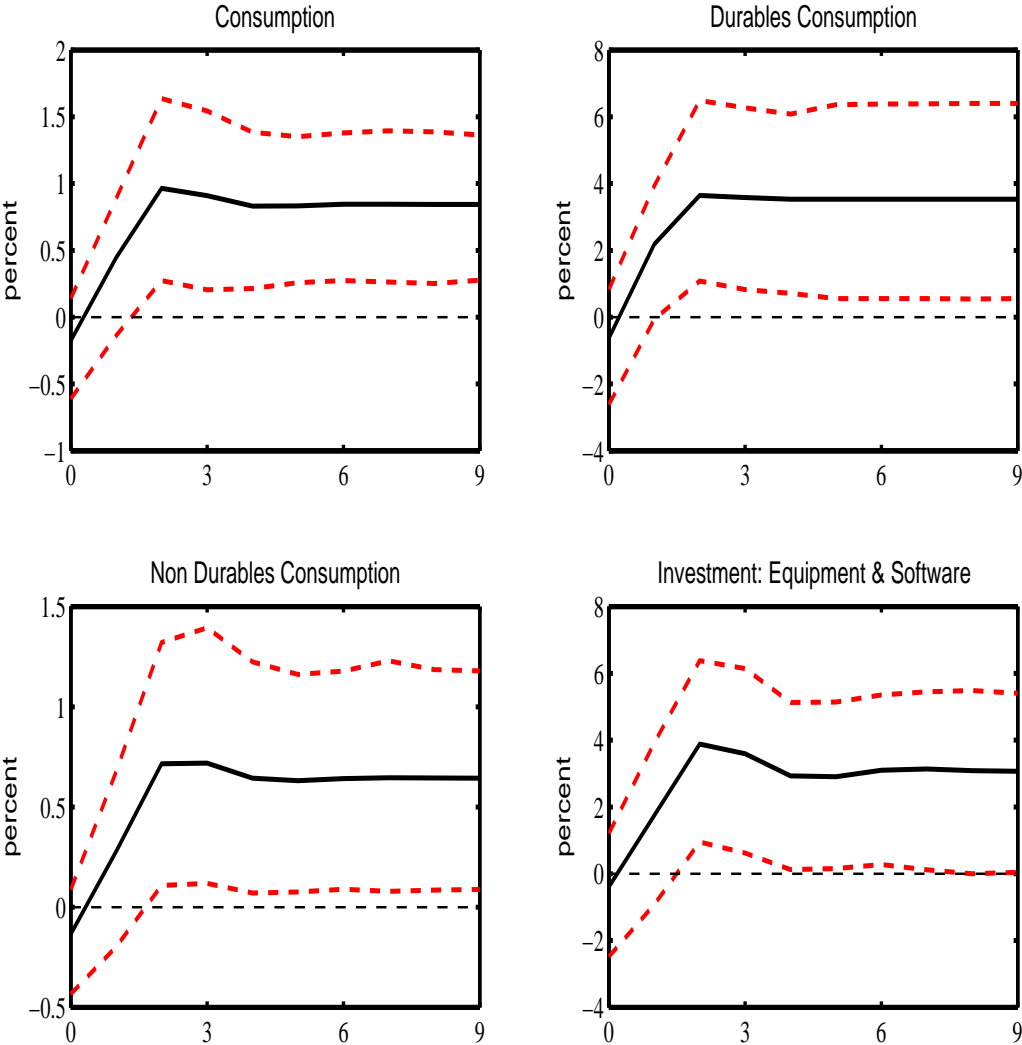


Figure 3.2: Impulse response functions: Responses of aggregate variables following a one-time realization of ICT innovations. Dashed (red) lines represent 90 percent non-parametric bootstrapped confidence bounds and the numbers on the horizontal axis correspond to years after the shock. The results are based on annual data from 1949 to 2007.



Figures 3.1 and 3.2 depict the dynamic behavior of TFP and other macroeconomic variables following an ICT innovation. I use the autoregressive coefficients and the coefficients on the measure of technical change, dated by adoption or commercialization, to compute the impulse response functions, along with a 90 percent non-parametric bootstrapped confidence bounds, for the variables depicted in figures 3.1 and 3.2. The focus on commercialization is warranted given that new technologies take time to diffuse through the economy. Therefore, to accurately capture the dynamic effects of technological change, one needs to start with when these technologies are successfully adopted.

As can be seen in figures 3.1 and 3.2, a one time realization of technological change leads to a contemporaneous jump in BFK TFP and labor productivity and no contemporaneous change in standard TFP. By the same token, output, consumption, hours worked and investment fall. The contemporaneous jump in BFK TFP, which is the “purified” Solow residual derived by Basu, Fernald and Kimball (2006), can be understood as the rise in the level of aggregate technology as most macroeconomists consider the variable to measure aggregate technology.

These contemporaneous responses, even though statistically insignificant, deserve a closer look. The zero effect on standard TFP, coupled with the fall in hours worked and output is more in tune with the sticky price model but with a twist. Traditionally, a positive technology shock leads to a fall in hours worked, following an improvement in TFP, leaving output unchanged. In this paper, improvement in the level of technology, measured by ICT innovations, does not contemporaneously show up in aggregate standard TFP, instead it shows up in BFK TFP. The fall in hours worked and output can be explained by firms overestimating the improvement in technology and reducing hours by more than is consistent with the actual change in technology. In a sticky price environment, this leads to a fall in output.

The long-run behavior is qualitatively similar for all the variables. In fact, innovations in ICT lead to a positive and significant long-run effect on the level of productivity, output, consumption and investment in equipment and software. The largest long-run level effect is on durable goods consumption and investment in equipment and software. The results for output, hours, and TFP in this paper differ from what Shea (1998) finds. In his paper, improvement in technology has effects consistent with the real business cycle literature, whereby the economy expands in that hours worked and output both rise.

The short and long-run responses to ICT innovations points to the relevance of embodied technological change. According to this theory, technological change has to be embodied in capital before it can affect output. This means that as time passes and as new capital that embodies the technology becomes available, output begins to rise.⁸

⁸See for example Greenwood et al. (1997), Greenwood and Jovanovic (1998), Hulten (1992) and Krusell (1998) for more on embodied technological change.

Table 3.1: Aggregate Results. Difference in R-squared from estimating the main aggregate equation with and without the new measure of technical change.

VARIABLES	R^2	ΔR^2
BFK TFP	0.13	28
TFP	0.05	24
Labor Productivity	0.10	93
Output	0.20	79
Consumption	0.14	60
Investment	0.14	85
Hours	0.18	100

Table 3.1 reports the incremental change in R^2 . I estimate the model with and without the indicator of technical change to obtain the difference in R^2 . The change in R^2 gives us an approximation of the contribution of ICT innovations to variations in the macroeconomic variables of interest. These results show that ICT innovations do not explain a large share of macroeconomic fluctuations. However, the medium and long run results presented here are economically important, indicating that technical change, proxied by the adoption of major ICT innovations, is an integral part of what is inside the TFP black-box. In the following subsection, I compare my results with those from earlier studies by embedding the direct measure of technology shocks in a Vector Autoregression (VAR).

3.1.4 Vector Autoregressions

Earlier studies often used Vector Autoregressions to evaluate the impacts of technology shocks. I therefore introduce the direct measure of technical change in a VAR to compare my results with those from earlier work.⁹

More specifically, the following bi-variate VAR is estimated for each macroeconomic variable:

$$Y_t = \alpha + Y_{t-p} + \epsilon_t$$

where $Y_t = [x_t, z_t]'$. As stated above, x_t stands for each of the macroeconomic variables that this study focuses on. In this section, x_t refers to the growth rate of TFP, output, investment, hours worked, consumption and labor productivity. The measures of TFP, output, hours worked and labor productivity are from the Bureau of Labor Statistics. Investment and consumption were obtained from the Federal Reserve Bank of Saint Louis's FRED database.

⁹Note that generally with count variables, the properties of the error term are different. The most efficient way to do VAR with count variables is to use MLE where the count nature of the variable is exploited. Given that I do not use MLE in my VAR, caution is in order when interpreting the results.

In each bi-variate VAR, recursive ordering is assumed. This means that a technology shock is identified as the residual component of the new indicator of technical change that is uncorrelated with the contemporaneous residual component of each of the macroeconomic variables. I estimate each system by setting p equal 2. This lag value is chosen based on the Bayesian Information Criterion (BIC), which in finite order performs better than the Akaike Information Criteria (AIC).

Figure 3.3: VAR impulse response functions: response of aggregate variables following a one-time realization of ICT innovations. In each case, a bi-variate VAR was estimated using 2 lags (chosen according to the Bayesian Information Criterion). TFP stands for total factor productivity and the dashed (red) lines represent 90 percent parametric bootstrapped confidence bounds. The numbers on the horizontal axis correspond to years after the shock. The results are based on annual data from 1949 to 2007.

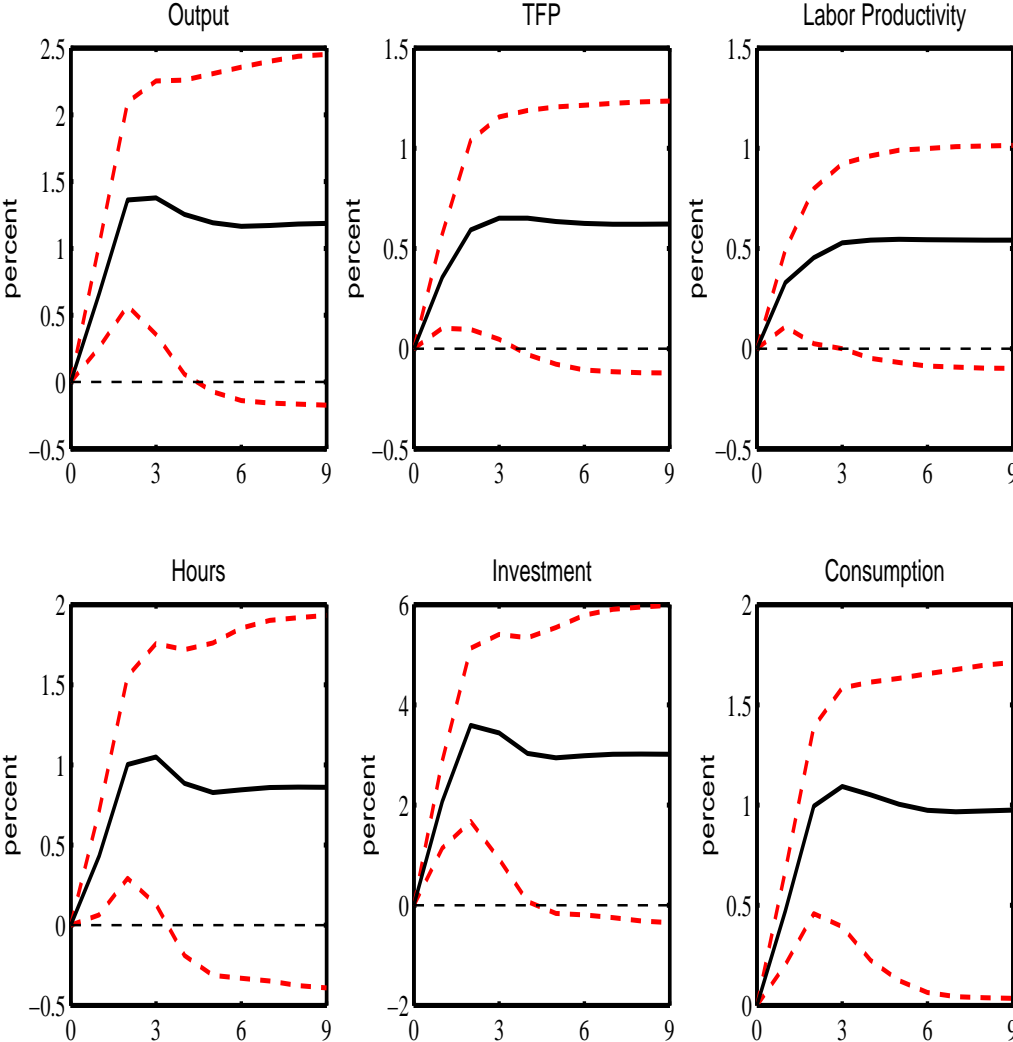
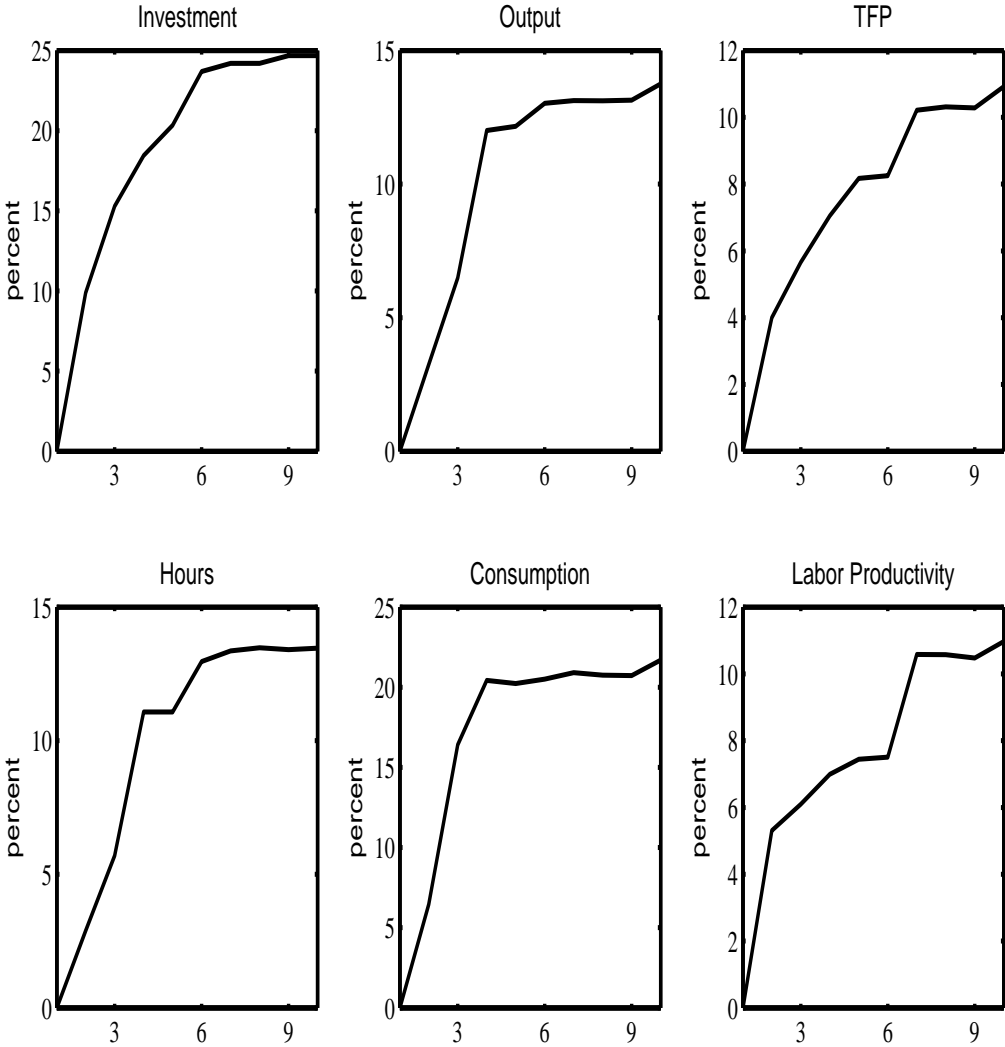


Figure 3.4: Shares of forecast error variance explained by the new indicator of technical change. In each case, a bi-variate VAR was estimated using 2 lags (chosen according to the Bayesian Information Criterion). TFP stands for total factor productivity. The horizontal axis corresponds to years after the shock. The results are based on annual data from 1949 to 2007.



From each bi-variate VAR, the impulse response function for the macroeconomic variable of interest to a technology innovation is computed. Also, the share of forecast error variance that can be attributed to the direct measure of technical change is obtained from estimating each bi-variate VAR. Figures 3.3 and 3.4 depict the impulse response functions and the shares of forecast error variances, respectively. To compare my results with earlier studies, I focus on one study that uses an indirect measure technical change, as in Basu et al. (2006), and another that uses a direct measure of technology, as in Alexopoulos (2010).

Figure 3.3 shows that the results are qualitatively and quantitatively similar to those obtained from estimating the simple autoregressive distributed lag model presented above. Following a one-time realization of ICT innovation, the level of output rises by more than 1 percent three years into the horizon. This result is similar to that found by Basu, Fernald, and Kimball (2006). Also, following ICT innovation, the level of TFP rises by close to 1 percent. Aside from the contemporaneous response of TFP in figure 4, the dynamic of TFP is also similar to that in Basu et al. (2006). Therefore, using different measures of technology, my findings for output and TFP are similar to those in Basu et al. (2006).

The responses of output and TFP are qualitatively similar to those presented in Alexopoulos (2010). However, the magnitude of the responses differ greatly. As shown in figure 4, the level of output rises by more 1 percent while the level of TFP rises by close to 1 percent. In Alexopoulos (2010), the responses of output and TFP to technology shocks are less than 0.02 percent. Despite both this study and Alexopoulos (2010) using direct measures of technology, the results presented in this paper are stronger.

Figure 3.4 shows the results of variance decomposition. The variations of each macroeconomic variable that can be attributed to ICT innovations are similar to those suggested by the changes in R^2 presented in the previous section. However, variance decomposition provides additional information. For example, ICT innovations explain 15 percent of variance in investment and consumption at business cycle frequency (3 years after the shock). In the long run, the share of variation in investment and consumption explained by ICT innovations increases to 22 and 25 percent, respectively.

ICT innovations do not explain a big share of fluctuations in output, TFP, labor productivity and hours worked, however. For example, at business cycle frequency the ICT innovations only explain 5 percent of variation in TFP. This is not surprising given that in the short run, much of the volatility in standard TFP can be explained by factors such as changes in utilization and composition Basu et al. (2006).

Overall, the results presented in figures 4 and 5 have the following economic implications. The impulse response functions indicate that technology shocks are important in the medium and long run while variance decomposition indicate that technology shocks, although non-negligible, are not the major drivers of economic fluctuations. This means that technology shocks take time to diffuse through the economy and that their initial impacts are not big enough to generate significant aggregate fluctuations.

In the section that follows, the impacts of the new measure of technology shocks at the sectoral level are evaluated.

3.2 Sectoral Implications

After evaluating the impact of ICT innovations on aggregate TFP and other macroeconomic variables, it is crucial to review sectoral TFP to determine whether sectors that use ICT capital more intensively benefit more from adopting new products and processes. Indeed, if major postwar ICT innovations have economic relevance, industries or sectors that use ICT capital more intensively would benefit more from these innovations.

The following subsections present the derivation of the specification used for that purpose.

3.2.1 Specification

To derive the estimating sectoral equation, I assume that each sector has a Cobb-Douglas production function of the form:

$$Y_{s,t} = A_{s,t} K_{s,t}^\alpha L_{s,t}^{(1-\alpha)}. \quad (3.3)$$

where Y , K , L , and A are value added output, capital, labor, and factor neutral technology, respectively. Taking logs on both side, equation (3.3) becomes

$$y_{s,t} = a_{s,t} + \alpha k_{s,t} + (1 - \alpha) l_{s,t}. \quad (3.4)$$

Suppose the growth rate of a variable X is equal to $\ln X_t - \ln X_{t-1} = x_t - x_{t-1} = \tilde{x}_t$. This means that equation (3.4) in growth rate becomes:

$$\tilde{y}_{s,t} = \tilde{a}_{s,t} + \alpha \tilde{k}_{s,t} + (1 - \alpha) \tilde{l}_{s,t}. \quad (3.5)$$

I Assume:

$$\tilde{a}_{s,t} = \alpha_s + \beta z_t + \delta r_{s,t} + \theta r_{s,t} * z_t + \tilde{u}_{s,t}. \quad (3.6)$$

where $\tilde{a}_{s,t}$ measures sectoral Solow residual (of sectoral TFP growth), z_t is an index of innovations in information and communications technology (ICT) consisting of the number of major ICT adopted in a given year, $r_{s,t}$ stands for ICT capital intensity which is the sectoral ratio of ICT capital to total capital, $\tilde{u}_{s,t}$ is a sectoral TFP disturbance, and α_s is a sector-specific constant term. Equation (3.6) implies that the impact of of ICT innovations on sectoral TFP growth is also a function of how much ICT capital a sector has as a ratio to its total capital.

From equation (3.6), one could argue that z_t is correlated with $\tilde{u}_{s,t}$ which would make estimating this equation problematic. Similarly, estimating an aggregate version of equation (3.6), which can be written as

$$\tilde{a}_t = \alpha + \beta z_t + \delta r_t + \theta r_t * z_t + \tilde{u}_t. \quad (3.7)$$

would suffer from the same problem. An example of these correlations could be that the

introduction of a major ICT innovation is always preceded by a high level of aggregate demand in which case estimating the effect of z_t on a_t would be biased. As a remedy to this bias, suppose that

$$\tilde{u}_{s,t} = \gamma_s \tilde{u}_t + \tilde{\xi}_{s,t}. \quad (3.8)$$

where sectoral TFP shocks, $\tilde{u}_{s,t}$, depend on an aggregate TFP shock, \tilde{u}_t , which is not related to NAE's major ICT innovations, and a residual component, $\tilde{\xi}_{s,t}$. By construction, $\tilde{\xi}_{s,t}$ and \tilde{u}_t are uncorrelated, which implies that $\tilde{\xi}_{s,t}$ is also uncorrelated with z_t . The zero correlation between \tilde{u}_t and $\tilde{\xi}_{s,t}$ is reasonable if we think of exogenous (non NAE innovations) aggregate technology shocks being independent of residual disturbances affecting sectoral TFP growth. The parameter γ_s measures the magnitude with which aggregate TFP shocks (not related to NaE's major innovations) are transmitted to sectoral TFP growth. From equation (3.7), we have

$$\tilde{u}_t = \tilde{a}_t - \alpha - \beta z_t - \delta r_t - \theta r_t * z_t. \quad (3.9)$$

Substituting equation (3.9) into (3.7) and then into (3.6) gives us:

$$\begin{aligned} \tilde{a}_{s,t} &= \alpha_s + \beta z_t + \delta r_{s,t} + \theta r_{s,t} * z_t + \gamma_s (\tilde{a}_t - \alpha - \beta z_t - \delta r_t - \theta r_t * z_t) + \tilde{\xi}_{s,t}. \quad (3.10) \\ &= (\alpha_s - \gamma_s \alpha) + \beta (1 - \gamma_s) z_t + \delta (r_{s,t} - \gamma_s r_t) + \theta (r_{s,t} - \gamma_s r_t) * z_t + \gamma_s a_t + \tilde{\xi}_{s,t}. \\ \tilde{a}_{s,t} - \gamma_s \tilde{a}_t &= (\alpha_s - \gamma_s \alpha) + \beta (1 - \gamma_s) z_t + \delta (r_{s,t} - \gamma_s r_t) + \theta (r_{s,t} - \gamma_s r_t) * z_t + \tilde{\xi}_{s,t}. \end{aligned}$$

Assuming that $\gamma_s = \gamma$, which means that the non-ICT aggregate technology shocks equally affect sectoral TFP growth, and moving $\gamma \tilde{a}_t$ to the right, we get the following equation:

$$\tilde{a}_{s,t} = \tilde{\alpha}_s + \beta (1 - \gamma) z_t + \delta (r_{s,t} - \gamma r_t) + \theta (r_{s,t} - \gamma r_t) * z_t + \gamma \tilde{a}_t + \tilde{\xi}_{s,t}. \quad (3.11)$$

where $a_{s,t}$ and a_t stand for sectoral and aggregate TFP growth. Aggregate TFP growth is a weighted average of sectoral TFP with weights being equal to an industry's value-added share. z_t , $r_{s,t}$ and r_t correspond to the new measure of technical change consisting of major ICT innovations, sectoral ratio of ICT capital to total capital, and aggregate ratio of ICT capital to total capital, respectively.

Equation (3.11) means that sectoral TFP is a function of relative ICT intensity and that adoption of new product and processes in information technology benefit TFP more in sectors that have a high value of this intensity. In the equation that follows, I assume that $\gamma = 1$. This specification assumes that any aggregate TFP shock affects TFP in each sector equally. The rationale for imposing this restriction relies on the fact that aggregate TFP is a weighted sum of sectoral TFP. Therefore, the sum of the sectoral responses to an aggregate TFP shock should add up to one.

$$\tilde{a}_{s,t} = \tilde{\alpha}_s + \delta (r_{s,t} - r_t) + \theta (r_{s,t} - r_t) * z_t + \tilde{a}_t + \tilde{\xi}_{s,t}. \quad (3.12)$$

In equation (3.12), the main coefficient of interest is θ . If positive and significant, the conclusion would be that ICT innovations lead to higher productivity in industries that use more ICT capital.¹⁰

3.2.2 Data

To estimate equation (3.12), the main variables are constructed as follows.

Value-added TFP growth

Value-added TFP growth for each sector is derived as follows:

$$\tilde{a}_{s,t} = \tilde{y}_{s,t} - \hat{\alpha}\tilde{k}_{s,t} - (1 - \hat{\alpha})\tilde{l}_{s,t}$$

For labor input, I use full-time employees by industry obtained from the BEA. The capital input measure is derived from the BEA's fixed assets tables, which contain 41 equipment assets and 15 structures assets types for 63 industries. Perpetual Inventory Method (PIM) is used to compute real capital stock for each asset type and in each sector using Fraumeni's (1997) delta for depreciation rates. Total real capital stock, for each industry, is simply the sum of the 56 types of capital in a given industry. More specifically,

$$K_{s,a,t} = (1 - \delta_a) * K_{s,a,t-1} + I_{s,a,t}$$

where K and I stand for capital and investment, respectively. And

$$K_{s,t} = \sum_{a=1}^{56} K_{s,a,t}$$

Subscript a and s refer to asset type and sector, respectively.

The number of industries in the BEA value-added data is different from the total number of industries in BEA fixed assets tables in that the former has 80 4-digit NAICS industries plus the private business sector while the later only has 63 4-digit industries. As a result, I construct 18 additional measures of real capital stock by aggregating the appropriate sub-industries.¹¹

ICT Intensity

¹⁰Note that this equation (3.12) is similar to the specification in Fernald 1999 with the difference being that I focus on ICT intensity as opposed to vehicle intensity.

¹¹The 18 industries are the following. Agriculture, forestry, fishing, and hunting; Mining; Manufacturing; Durable Good Manufacturing; Non-durable Good Manufacturing; Transportation and Warehousing; Information; Finance, Insurance, and Real Estate; Finance and Insurance; Real Estate and Rental Leasing; Professional and Business Services; Administrative and Waste Management Services; Educational Services, Health Care, and Social Assistance; Health Care and Social Assistance; Hospital and Nursing and Residential Care Facilities; Art, Entertainment, and Recreation; Accommodation and Food Services.

ICT capital stock is obtained by aggregating the different types of ICT capital stock.¹² An industry ICT intensity is measured as the ratio of real ICT capital stock to real total capital stock. Therefore, for each sector,

$$r_{s,t} = \frac{K_{s,t}^{it}}{K_{s,t}}$$

where $K_{s,t}^{it}$ stands for ICT real capital stock.

Relative Productivity and Relative ICT intensity

Relative productivity (rp) consists of the difference between an industry's TFP growth and a weighted sum of other industries TFP at a given point in time. The weights used here are industries' share of nominal value added to total value added. More specifically:

$$rp_{s,t} = a_{s,t} - \sum_s w_{s,t}(a_{s,t}).$$

$$rp_{s,t} = a_{s,t} - a_t.$$

where

$$w_{s,t} = \frac{VA_{s,t}}{VA_t}.$$

Similarly, relative ICT intensity ($rr_{s,t}$) is measured as

$$rr_{s,t} = r_{s,t} - \sum_s w_{s,t}(r_{s,t}).$$

$$rr_{s,t} = r_{s,t} - r_t.$$

¹²These are: Mainframes, PCs, DASDs (Direct Access Storage Device), Printers, Terminals (for controlling multiple connections simultaneously), Tape Drives, Storage Devices, System Integrators, Prepackaged Software, Custom Software, Own Account Software, Communications, and Photocopy and Related Equipment.

Table 3.2: The 19 sectors used in the estimation (in no particular order).

Sectors
Agriculture, forestry, fishing, and hunting
Mining
Utilities
Construction
Nondurable goods
Durable goods
Wholesale trade
Retail trade
Information
Finance and insurance
Real estate and rental and leasing
Professional and business services
Management of companies and enterprises
Administrative and waste management services
Educational services
Health care and social assistance
Arts, entertainment, and recreation
Accommodation and food services
Other services, except government

3.2.3 Results

The basic idea behind the estimation of the restricted model is to evaluate the relative importance of ICT capital in the presence of new product and process innovations under the conditions that any non ICT technology aggregate shock affects sectoral TFP with equal magnitude. This boils down to assuming $\gamma = 1$. The model is estimated using pooled cross-section time series regression on a sample of nineteen different sectors of the economy spanning from 1949 to 2007.

Table 3.3 presents the results for four different industry groupings. In addition to the full sample, I estimate the restricted model by excluding the information and farm sectors; information, farm, mining, and durable goods sectors; and information, farm, and mining sectors. The goal of this approach is to see whether results vary dramatically as we move from one group to the next.

The coefficient of interest is θ and this coefficient is positive as expected meaning that ICT innovations have a positive impact on relative TFP at the sectoral level. However, for a more thorough interpretation of the results, consider the first column of table 3, associated

Table 3.3: Restricted model estimation results. IG stands for industry grouping. The numbers below the coefficients are standard errors. The model is estimated using a pooled time series cross-section regression. The star(s) next to the coefficients indicates significance level (1 star = significant at the 10 percent level, 2 stars = significant at the 5 percent level and 3 stars = significance at the 1 percent level).

IG	All Sectors	Excluding Information and Farm	Excluding Information, Farm, Mining, and Durable Goods.	Excluding Information, Farm and Mining.
θ	0.21* (0.12)	1.06* (0.60)	0.81* (0.45)	1.00* (0.53)
δ	0.46 (1.70)	1.83 (1.61)	0.98 (1.52)	1.30 (1.52)

with the full sample results. From that column, $\theta = 0.21$. This means that if a sector has a one percentage point higher ratio of ICT capital to total capital relative to sectoral average, its TFP would improve by 0.21% more. This is roughly similar, quantitatively, to what Alexopoulos (2010) finds the effect of computer technology to be on TFP.

The overall interpretation is that ICT innovations improve relative productivity in sectors that use IT capital more intensively. This result has implications for existing work that focuses on the role of ICT capital in spurring TFP growth. As described in the introduction, two main views dominate this debate.

The first is the neoclassical growth theory which predicts that the use of ICT capital leads to capital deepening and a rise in labor productivity in sectors that use this capital. For this theory, only ICT producing sectors would see their TFP growth improve. The second view comes from the general purpose technology literature which predicts that sectors using ICT capital do benefit in terms of TFP growth. This is because use of ICT capital leads to fundamental changes in the production process of sectors using the new inventions allowing firms to deploy their other inputs in more productive ways. As Basu and Fernald (2007) have shown, the use of ICT capital does lead to TFP growth in industries using ICT more intensively. The result presented in this chapter adds to this evidence by showing that the adoption of new ICT adds more to the TFP gains in industries that use ICT capital.

3.3 Conclusion

This chapter shows that technological progress - measured by major innovations in information technology - has important implications for TFP and other key macroeconomic variables.

Results show that the direct measure of technology shocks presented in chapter 2 has positive and significant effects on aggregate TFP, output, consumption, and investment. Using VAR produces similar macroeconomic dynamics in that the responses of all the macroeconomic variables to ICT innovations are similar to those found using a simple autoregressive distributed lag model. Variance decomposition indicates that technology shocks do not explain a big share of macroeconomic fluctuations.

To corroborate the aggregate impacts of the new measure of technical change, I investigate whether sectors that use ICT capital more intensively see their productivity benefit by more. Such a relationship would hold if the major ICT innovations identified by the NAE have important economic implications. The key finding is that industries that use ICT capital more intensively benefit by more, in terms of productivity, from adopting the new technology.

Chapter 4

ICT Innovations and Market Reactions

[I]magine trying to rewrite the Great Contraction chapter of *A Monetary History* with shocks of this kind playing the role Friedman and Schwartz assign to monetary contractions. What technological or psychological events could have induced such behavior in a large, diversified economy? How could such events have gone unremarked at the time, and remain invisible even to hindsight? (Lucas, 1994, 9)

The major inventions identified by the NAE are events which have important economic implications. This begs the following questions. Did market participants or investors know about these innovations and their potential? Or as Lucas (1994) said, have these innovations “gone unremarked”? To answer these questions, this chapter first summarizes the contemporaneous evidence of investors’ enthusiasm following the introduction of such inventions before examining whether stock prices, measured by the S&P 500, respond to such enthusiasm. If the S&P 500 is significantly affected by the direct measure of technical change, whether negatively or positively, this would be formal evidence that market participants do respond to expectations about future improvements in TFP.

An example of narrative evidence is the market reactions to the first major postwar ICT innovation isolated by the NAE, the transistor. Introduced in 1948 and commercialized in 1951 when it was used in a hearing aid, the potential applications of this technology were recognized early as evinced in a July 1, 1948 *New York Times* article. It was noted in that article the transistor would have “several applications in radio” (quoted in Hawkins (1999)).

This chapter first summarizes the narrative evidence before presenting informal and formal evidence of stock price response to technical change.

4.1 Market Reactions: Narrative Evidence

The fifty-four ICT innovations isolated can be categorized into four major phases of technical change. The first is the electronics revolution, which was launched by the introduction

of the transistor and which arguably culminated with Intel's introduction of the microprocessor. The second is the personal computer phase with IBM PC and Apple's Macintosh. The third phase refers to the beginning of the commercialization of cellular phones and the fourth phase began in the early 1990s with the Internet going public.

Given these phases, an interesting question is whether market participants saw these innovations coming or whether they realized their potential benefits at the time the innovations were being introduced. My reading of the historical record not only suggests that market participants were aware of the potential long-run benefits, it also indicates that most of the major innovations discussed here were pervasive and led to the creation of new industries. I summarize this narrative evidence in the subsections that follow.

4.1.1 Electronics Revolution and Personal Computing

The Transistor

A couple of years after WWII, three ATT Bell Laboratories scientists invented the point-contact transistor. Up to this point, the world of electronics was dominated by the vacuum tube which used excessive electricity and performed slowly. The following excerpt demonstrates the importance of such an invention:

Most experts agree that the greatest postwar breakthrough for industry was neither plastics nor nuclear energy but the transistor, a speck of silicon or germanium with spider-wire legs, first demonstrated at the Bell Telephone Laboratories in 1947. From this invention, which in essence offered a new way to control and amplify electric signals, sprouted the great tree of the electronics industry.¹

In the following year, in 1948, a patent was filed for the invention and on the first of July of the same year, the New York Times announced the invention of the transistor. Here is an excerpt of the announcement (from Arns, 1998):

A device called a transistor, which has several applications in radio where a vacuum tube ordinarily is employed, was demonstrated for the first time yesterday at Bell Telephone Laboratories ... The device was demonstrated in a radio receiver, which contained none of the conventional tubes ...

There is still an ongoing debate about who should receive credit for the invention of the transistor and when it came into existence for the first time. For the preliminary analysis, I use the New York Times announcement date (July, 1948).

¹New products of industry and changes in markets. (1962). In *Editorial research reports 1962* (Vol. II). Washington: CQ Press. Retrieved March 31, 2009, from CQ Press Electronic Library, CQ Researcher Online, <http://library.cqpress.com/cqresearcher/cqresrre1962091200>

The Integrated Circuit

Until 1958, the circuitry of electronics operated through different parts. This required the different components to be built separately before joining them using switches and wires to make them work. At the time, such tasks were onerous. In September of 1958, Jack Kilby of Texas Instruments invented the integrated circuit. Kilby realized that resistors, capacitors and transistors and diodes can all be put together on a single piece of silicon. One year later, in 1959, Robert Noyce of Fairchild Semiconductor improved upon Kilby's idea by building a more advanced integrated circuit . This was a major step in the world of electronics and computing:

The next big breakthrough in computer technology came in 1959 when scientists at Texas Instruments and Fairchild Camera and Instrument Co. simultaneously developed the integrated circuit, what Colin Norman called "the centerpiece of microelectronic technology" (Constable and Somerville, 2003).

Intel's 4004 Microprocessor

Widely known as 'computer on a chip', the Intel 4004 microprocessor was the first of its kind. Intel officially announced the invention of the 4004 as an add in the November 15, 1971 issue of *Electronic News* reading "Announcing a new era of integrated electronics." An Earlier, non-official, announcement appeared in the May issue of *Datamation*. Around the same time, Texas Instruments also announced its central processing unit on a chip but Intel's micro-chip is recognized as the first "computer on a chip" technology. The versatility of a microprocessor can be illustrated by the following quote from Constable and Somerville.

The flexibility of the offerings had enormous appeal. If for instance, the maker of a washing machine or camera wanted to put a chip in the product, it wasn't necessary to commission a special circuit design, await its development, and shoulder the expense of custom manufacturing. An inexpensive, off-the-shelf microprocessor guided in its work by appropriate software, would often suffice. These devices, popularly known as a computer on a chip, quickly spread far and wide. (Constable and Somerville, 2003, 56)

Altair 8800

In its January 1975 issue, the front cover of *Popular Electronics* read "Project Breakthrough! World First Minicomputer Kit to Rival Commercial Models ... Altair 8800". This is widely accepted as the first home computer Constable and Somerville (2003). On page 33 of the same issue, *Popular Electronics* went on to say that "The era of the computer in every home - a favorite topic among science-fiction writers - has arrived!" and "In many ways, it represents a revolutionary development in electronic design and thinking."

4.1.2 Approval of the Commercial Cellular Phone Services

The approval of the commercial cellular phone services by the government led investors to expand in anticipation of the foreseeable benefits. The following quotes give us a glimpse of some of this enthusiasm:

Jack Hurley, manager of General Electric's cellular communications, declared cellular phones to be:

(A) Scientific breakthrough that would become the wave of the future Mayer (1982)

... an extremely lucrative opportunity, with large volume that ... will grow to a \$1 billion a year industry Mayer (1982).

Tom Guzek, a regional manager for an electrical supply firm, was quoted in *The New York Times*, June 23, 1985 article saying:

What used to be dead time away from the office, is now productive time Graff (1985)

4.1.3 Internet Going Public

Similar enthusiasm characterized investors and market participants when the Internet went public. For example, Douglas Colbeth, then President of Spyglass Inc, was quoted in *Newsbytes*, October 24, 1994 saying:

Companies understand the benefits of the Internet and how they can use it to expand their markets, provide better customer service, and improve employee communications Staff (1994c)

and Bill Oliver, then AT&T Corporate VP for public relations, was quoted in the same *Newsbytes*'s article saying:

The Web has improved our operations and made internal communications more productive Staff (1994c)

4.2 Market Reactions: Informal Evidence

For companies that have introduced, or that were affected by the adoption of, the innovations, measures of daily stock price were obtained from the Center for Research in Security Prices (CRSP) available at the Wharton Research Data Services. Data availability restricted

the attention to seven companies directly or indirectly involved with the innovations.² In addition, I use the S&P 500 index to gauge the overall market reaction.

²The companies include Motorola Inc. (MOT), International Business Machines (IBM), MCI Communications (MCIC), Union Carbide Corporation (UK), Lucent Technologies (LU), Apple Computer Inc. (AAPL), and American Telephone and Telegraph (AT&T).

Figure 4.1: Firm-level Stock Price (logged) following innovation announcements

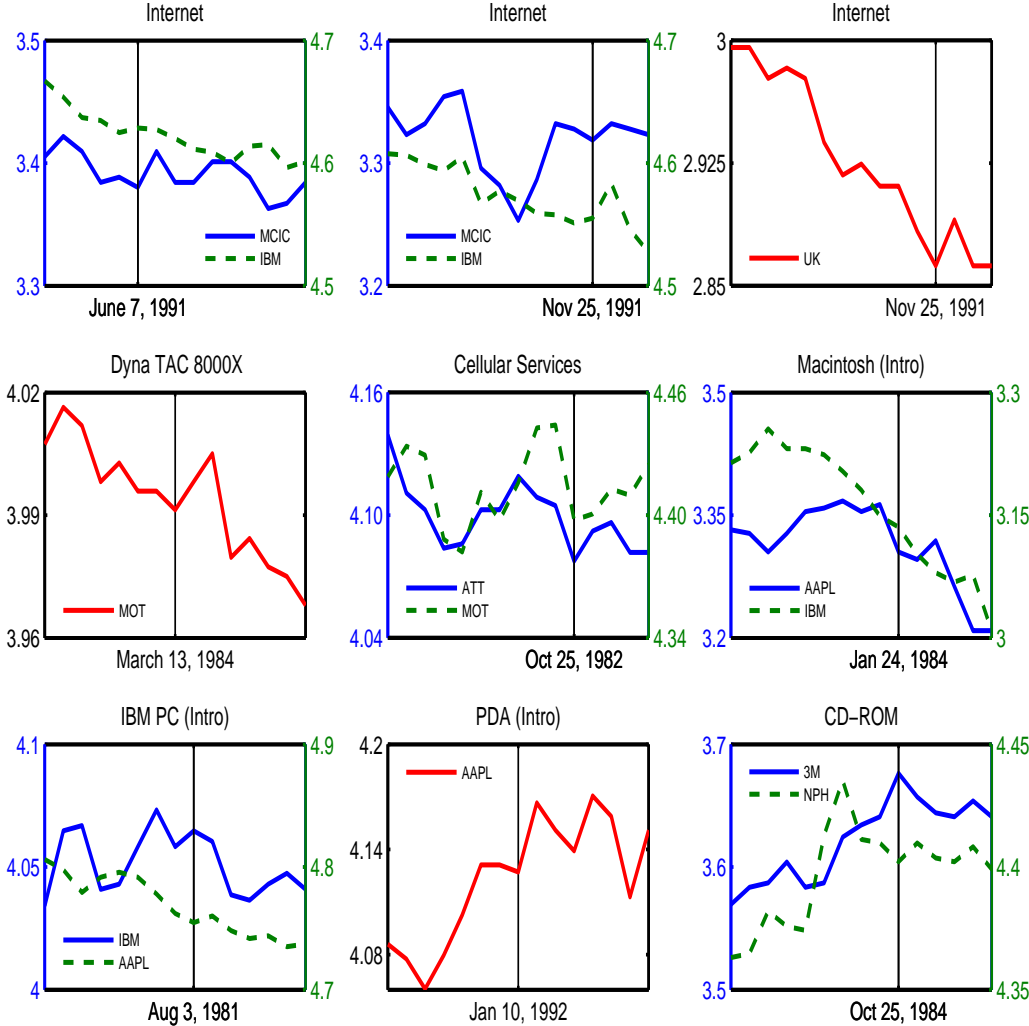
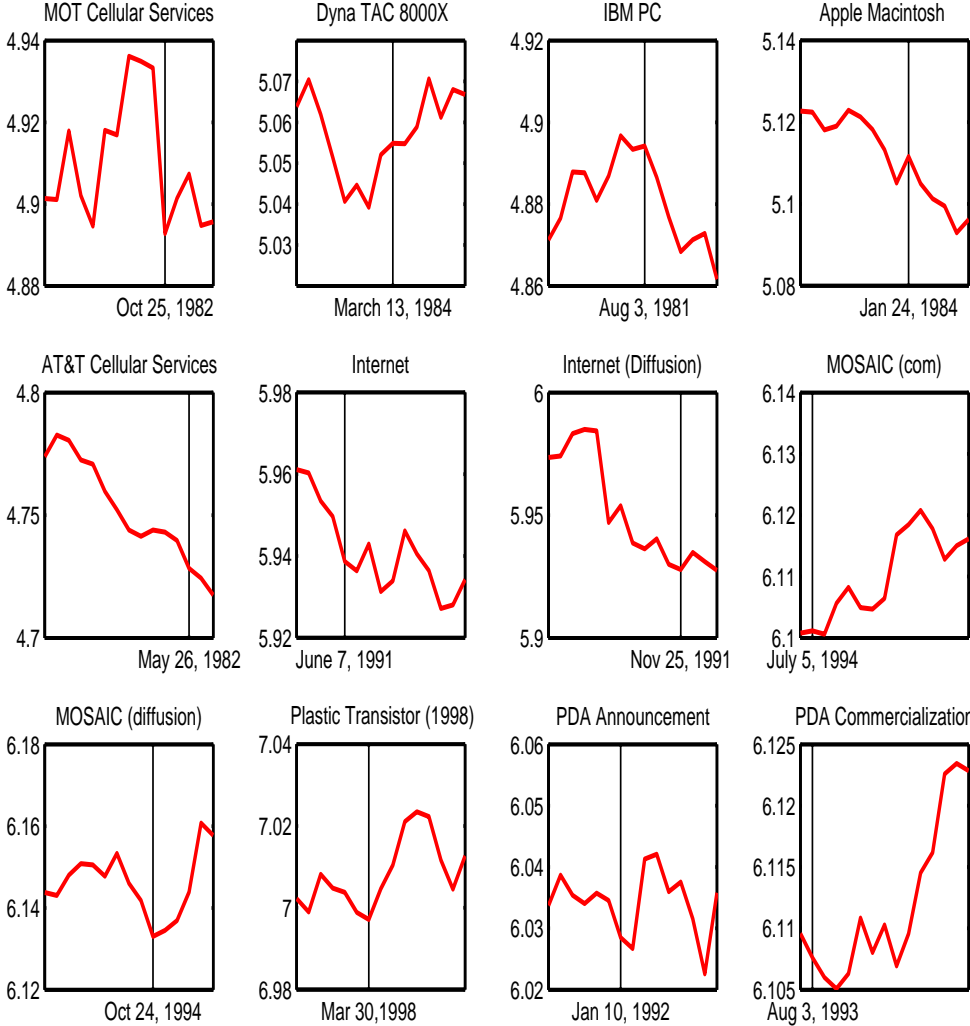


Figure 4.2: Behavior of the S&P 500 around innovation announcements



In most cases, the stock price of these firms responded positively following the announcement. Figure (4.1) shows the response of stock price of IBM, Union Carbide Inc (UK), and MCI Communications (MCIC), Motorola, AT&T, and Apple following either an introduction of a new product, as in the case of IBM PC, or the commercialization of the Internet, after which IBM, MCIC, and UK entered the market because of the foreseeable benefits Anthes (1991).

In addition, figure (4.2) shows the behavior of the S&P 500 around the time these announcements were made. There is no consistent positive response of the S&P 500 to these announcements.

4.3 Market Reactions: Formal Evidence

To formally determine whether technological innovations affect stock prices, the following equation is estimated:

$$sp_t = \alpha + \sum_{i=1}^p \sigma_i sp_{t-i} + \sum_{i=0}^d \delta_i z_{t-i} + \epsilon_t$$

This equation assumes that the dynamics of aggregate measure of stock prices (sp_t) is determined by its past history and by the new direct measure of technical change and its lags (z_{t-i}). Stock prices can be affected by other factors. However, I assume that these factors, captured by ϵ , are not correlated with the measure of technical change. The equation is estimated using OLS. The measure of stock prices used is the real per capita S&P 500 and comes from Beaudry and Lucke 2009.

OLS results show that ICT innovations have a negative and significant contemporaneous effect on stock prices but positive and insignificant cumulative effect. Indeed, the contemporaneous coefficient of the new measure -0.04 and is significant at the 10 percent level. And, the sum of all the coefficients of the technology variable is 0.04 and I could not reject the null hypothesis that this sum is equal to zero. These results cast doubt on the predictions of the expectations driven business cycle theory. If information about future improvements in TFP is embedded in stock prices, we should see the measure of stock prices positively respond to innovations that positively affect TFP. The fact that the S&P 500 contemporaneously falls in response to these innovations suggests that stock prices cannot be used to infer future changes in productivity.³

³The finding that stock prices fall following ICT innovations is more in line with the response of stock prices to information technology presented in Jovanovic and Hobijn (2001).

4.4 Concluding Remarks

Despite being an important variable in macroeconomics, total factor productivity (TFP) is still a black box. Unfortunately, existing approaches use technology measures that do not satisfactorily measure true technical change.

In this thesis, I introduce a new measure of technical change. This measure consists of actual inventions in information technology identified by engineers who are technology experts. With this new measure, I present fresh evidence that technical change affects TFP and other key macroeconomic variables. This evidence can be summarized as follows.

First, technology shocks - measured as major inventions in information and communication technologies have positive and significant effects on aggregate TFP, output, consumption, and investment. The contemporaneous effect on TFP is zero, while that on hours and output is negative. This result differs from what is found in the existing literature. From the perspective of real business cycle theory, a positive technology shock raises both productivity and output along with labor input. In a baseline sticky price model, technological improvement leads to higher productivity, lower labor input and an unchanged level of output. Although it is hard to determine the contemporaneous effect from low frequency data, one plausible explanation of the contemporaneous results presented in this chapter is that firms overestimate the importance of technical change and lower labor input by more than optimal, which in the presence of sticky prices may lead to lower output. Another explanation is that technological change has to be embodied in new capital before it can affect output. This explains the insignificant contemporaneous response as well as the slow build-up in output and other variables.

Second, using VAR produces similar macroeconomic dynamics in that the responses of all the macroeconomic variables to ICT innovations are similar to those found using a simple autoregressive distributed lag model. Variance decomposition indicates that technology shocks do not explain a big share of macroeconomic fluctuations. Overall, the aggregate implications of technology shocks are that they have important and positive medium and long run effects.

Third, and to corroborate the aggregate impacts of the new measure of technical change, I investigate whether sectors that use ICT capital more intensively see their productivity benefit by more. Such a relationship would hold if the major ICT innovations identified by the NAE have important economic implications. I find that industries that use ICT capital more intensively benefit by more, in terms of productivity, from adopting the new technology.

Fourth, narrative evidence suggests that the introduction of major inventions lead market participants to react positively in anticipation of future improvements in productivity. An informal test of whether company-level stock prices react consistently and positively to the introduction of the invention did no produce convincing results, however. A formal test of whether the aggregate S&P 500 significantly responds to technology shocks shows that stock prices fall following technology shocks, a result consistent with the finding by Jovanovic and Hobijn (2001).

Overall, the results presented in this thesis call for further analyses of the effects of ICT innovations on TFP and on other key macroeconomic variables. First, the approach presented in this thesis can be used to investigate whether cross-country variations in ICT capital, combined with the adoption of information technologies, can explain cross-country differences in TFP. More specifically, do countries with a higher ratio of ICT capital to total capital see their productivity rise by more, relative to countries for which this ratio is low, by adopting new ICT? Earlier work has looked at why some countries lagged behind in terms of productivity gains from information technology. Examples include Basu et al. (2003) and Bresnahan et al. (2002). Second, the approach can be extended to analyze the effect of other types of technical change on productivity. This includes, but not limited to, focusing on energy-saving technologies and evaluating their growth implications.

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